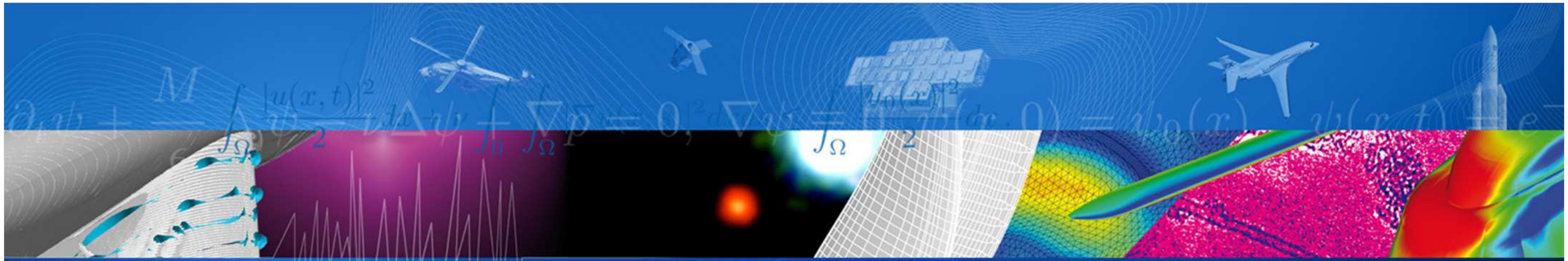


Status and Challenges of CFD at Onera

prepared by the Fluid Mechanics Branch

Presented by
Vincent Couaillier

CFD & Aeroacoustics Department

ONERA

THE FRENCH AEROSPACE LAB

return on innovation

CFD softwares in aerodynamics for industrial applications

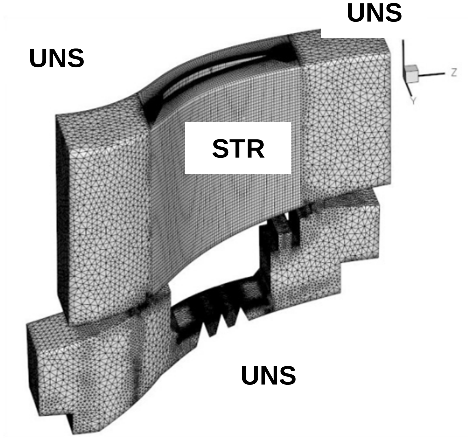
- Transfer innovative CFD technology to industrial partners in aerospace

  - Airbus Group, Dassault

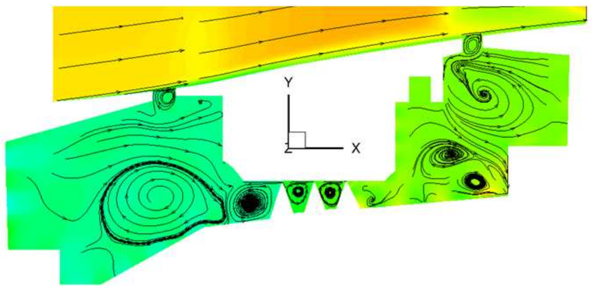
  - Safran Group (Snecma, Turbomeca, Techspace Aero)

- Provide softwares (elsA for aerodynamics, Cedre for energetics) and expertise to aerospace industry with direct assistance

- Main industrial customers :
  - Aircrafts and helicopters : Airbus, Airbus-Helicopter
  - Turboengines : Safran Group
  - EDF for turbines

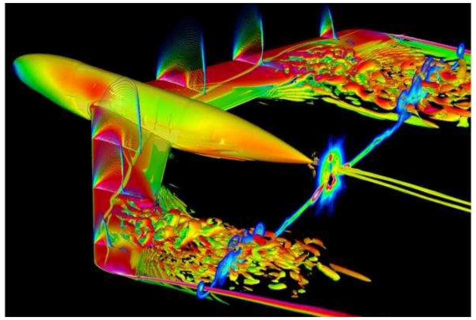


Hybrid mesh to be provided by Safran



elsA-H RANS-Kω computation ONERA/DSNA

elsA DES computation ONERA/DAAP



OUTLINE

A – Status and on-going developments

- Status of elsA code
- Brief status of Cedre Code

B- Some challenges

- Meshing strategies (for complex geometries) in relation with
  - Hybrid structured/unstructured solver
  - High order accuracy : Aghora DG prototype
- Hybrid HPC and heterogeneous plate-forme for CFD

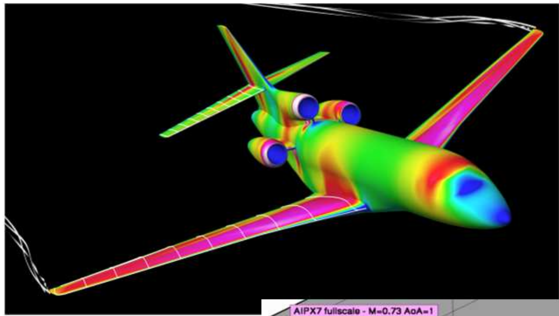
C- Some elements of Onera CFD roadmap

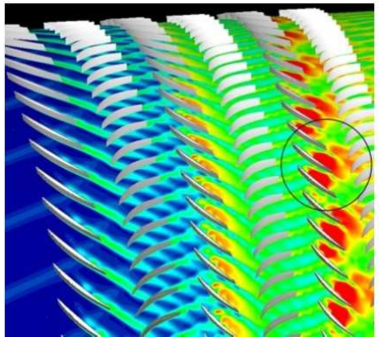
- New generation of software development

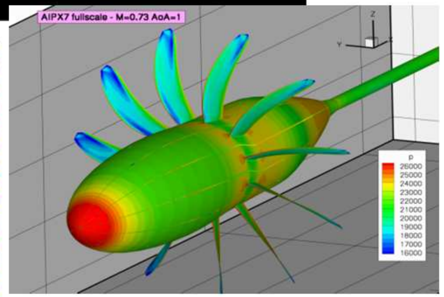
elsA: general description (1/2)

Multi-purpose CFD simulation platform

- Internal and external aerodynamics
- From low subsonic to high supersonic
- Compressible 3-D Navier-Stokes equations
- Moving deformable bodies
- Aircraft, helicopters, turbomachinery,
- CROR, missiles, launchers…

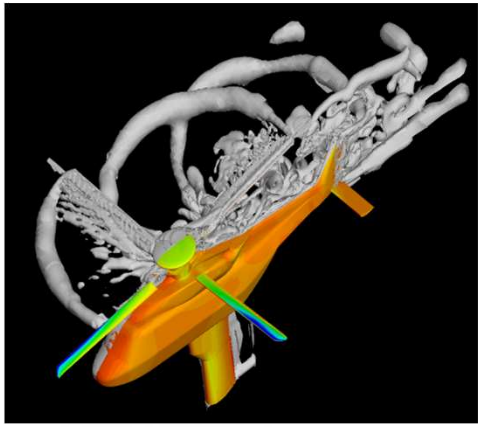






Design and implementation

- Object-Oriented
- Kernel in C++/Fortran
- User interface in Python
- Python-CGNS interface for CGNS extraction and coupling with external software



L. Cambier, S. Heib, S. Plot, The Onera elsA CFD software : input from research and feedback from industry, Mechanics & Industry, 14(3): 159-174

elsA: general description (1/2)

Physical modeling

- RANS or URANS + turbulence and transition modelling
- DES, LES

Multiple-gridding strategy

- High flexibility in multiblock structured body fitted approach : coincident or partially coincident, totally non-coincident, Chimera overset grids…
- Extension to hybrid grids with both structured and unstructured blocks
- Adaptive Cartesian grids

Numerics

- Cell-centred finite volume (2^{nd} order and higher order methods adapted to structured grids)
- Upwind or centred schemes
- Backward Euler technique with implicit (LU relaxation methods)
- Multigrid techniques
- Dual time stepping for time accurate unsteady simulations
- Harmonic Balance Technique for time periodic flows

Calculation of sensitivities (linearized equation, adjoint solver techniques)

Aeroelasticity

elsA software : Research partners and industry users

Onera and research partners

- Several Onera departments involved in basic CFD research, software production, validation for internal and external aerodynamics (aeroacoustics, aeroelasticity…)
- Cerfacs (*Toulouse*) : mesh strategies, numerical methods, CPU efficiency…
- Dynfluid (Arts et Métiers ParisTech) : high accuracy numerical methods
- LMFA - Fluid Mechanics and Acoustics Lab (*Ecole Centrale de Lyon*) : turbomachinery validation…
- Cenaero (*Belgium*) : turbomachinery validation, aerothermics…
- Von Karman Institute (*Belgium*) : turbomachinery validation

Industry users

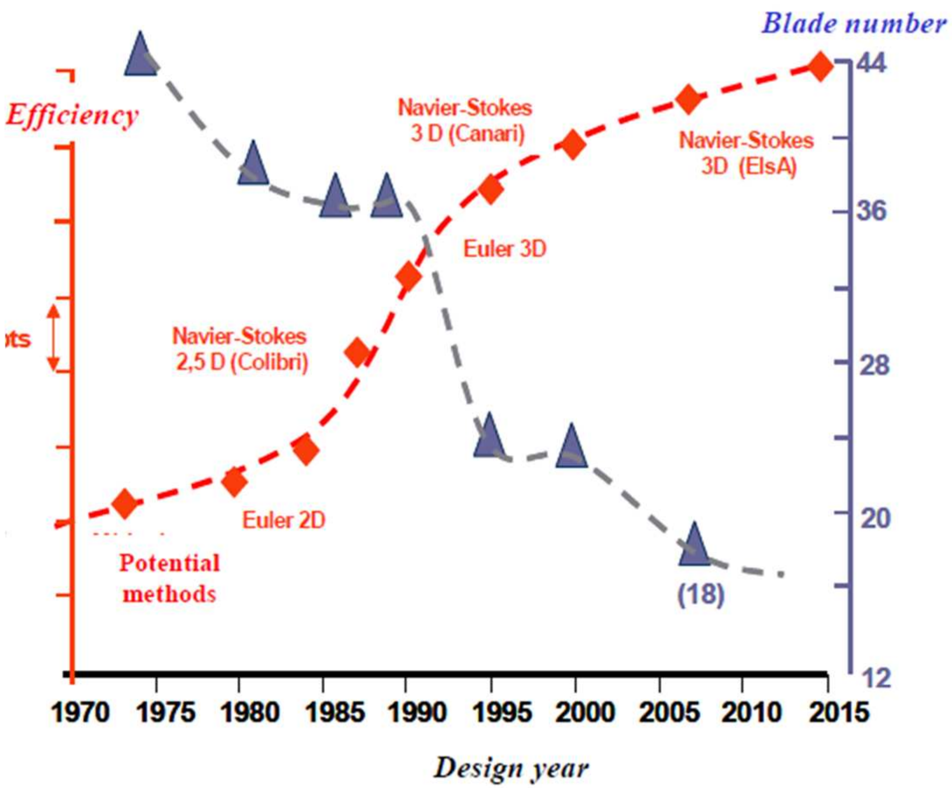
- Airbus : transport aircraft configurations
- Safran (*Snecma, Turbomeca, Techspace Aero*) : turbomachinery flow simulations
- Airbus-Helicopter for helicopter applications

+ MBDA (missile configurations), Electricité de France (steam turbines)…

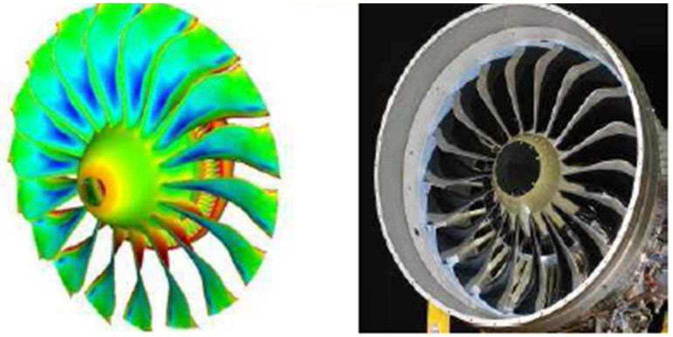
Cooperations with schools : *elsA* as a training tool

Ecole Polytechnique Palaiseau, EPF Sceaux, ISAE Toulouse, Universities…

Contribution of CFD to fan efficiency (courtesy of Safran/Snecma)

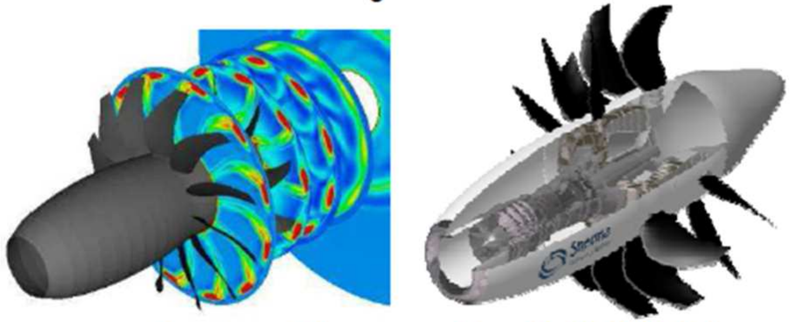


Simultaneous progress of the efficiency
(+ 10 points in 30 years)
and of the decrease of the number of blades
(2xless blades)
… and extension to counter rotating concepts



Modern fan with 18 blades

Counter rotating fan with 10 + 14 blades



Counter rotating open rotor with 12 + 10 blades

Results of elsA simulations from Snecma

Transport aircraft results with elsA (1/2) (courtesy of Airbus)

- Navier-Stokes CFD introduced for many years in Aerodynamic Design and Data processes of Airbus

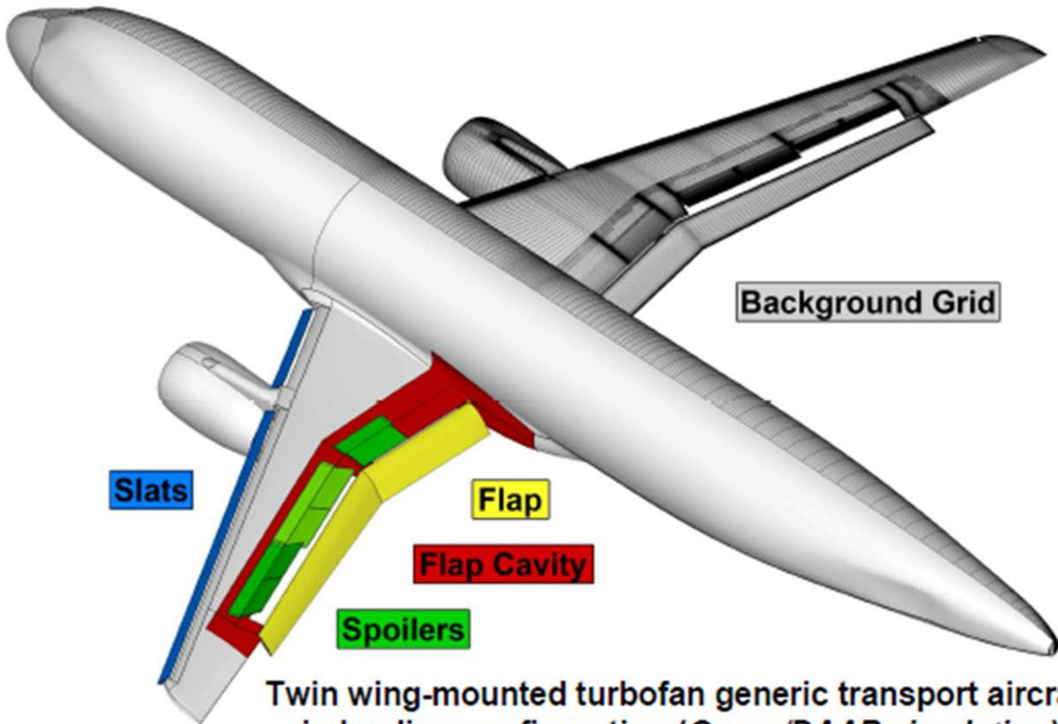
→ Quickly deliver more optimized aerodynamic shapes of aircraft components ;

→ Evaluate Re effects, jet effects, ground effects by extrapolating results on an existing aircraft ;

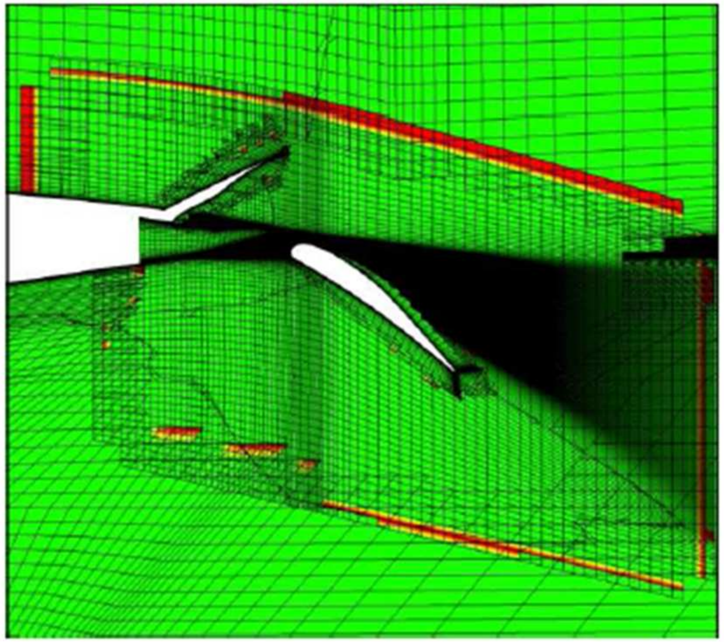
→ Prepare, analyse, and, if necessary, correct wind tunnel and flight tests.

- Airbus uses *elsA* as its structured multi-block tool

→ Massive ramp up of the use of Chimera overset grids: *control surface applications*, antenna on fuselage, wing tip effect, Vortex Generators, landing gear cavity …

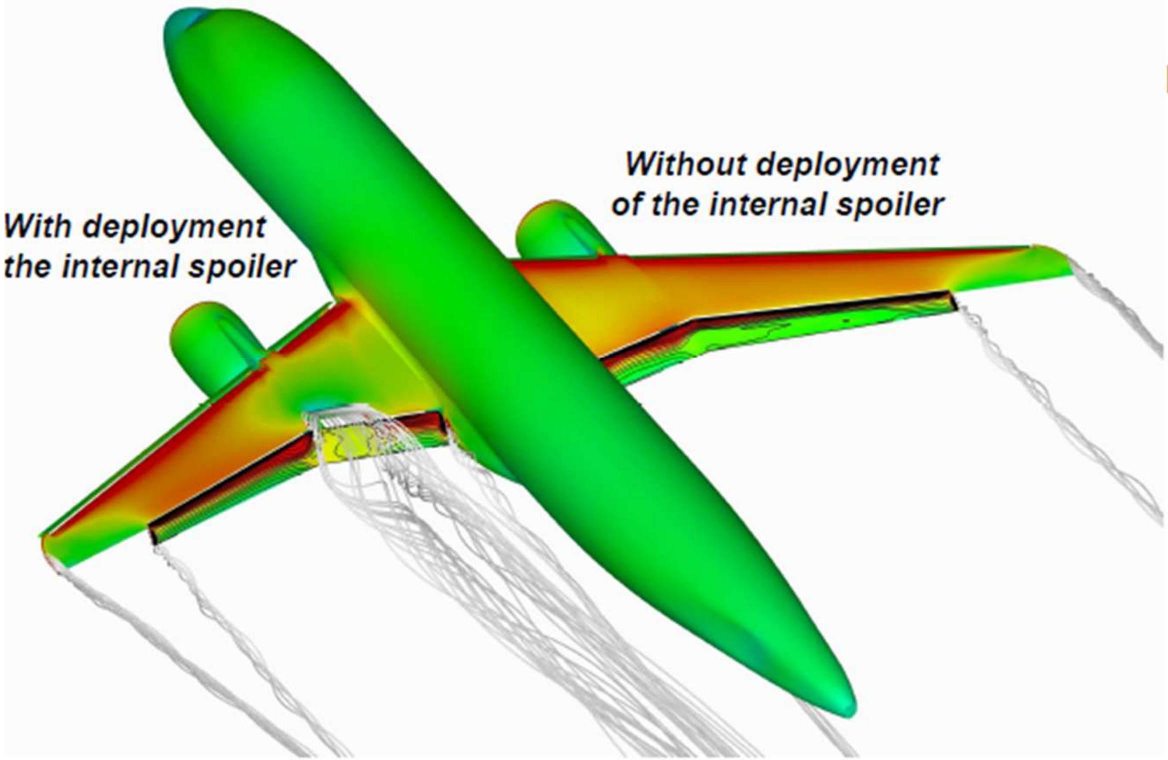


Twin wing-mounted turbofan generic transport aircraft in landing configuration (*Onera/DAAP simulation)*



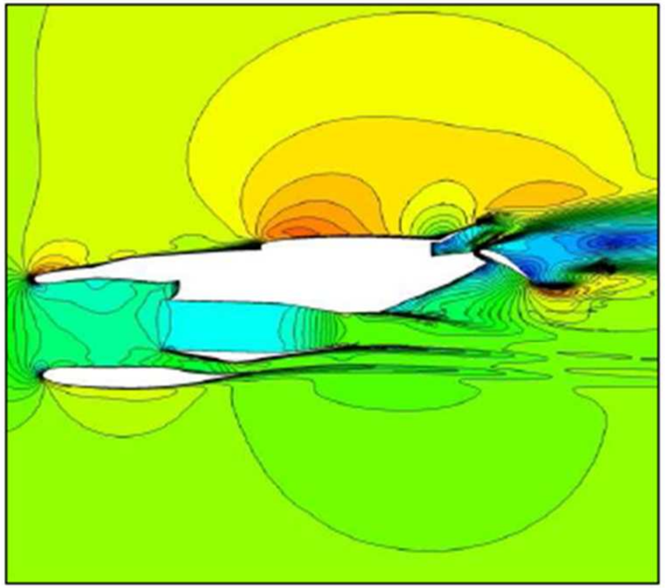
More than 140 blocks and 33 million mesh points

Transport aircraft results with elsA (2/2)
Twin wing-mounted turbofan aircraft in landing configuration



RANS + Spalart-Allmaras simulation

Pressure coefficient field

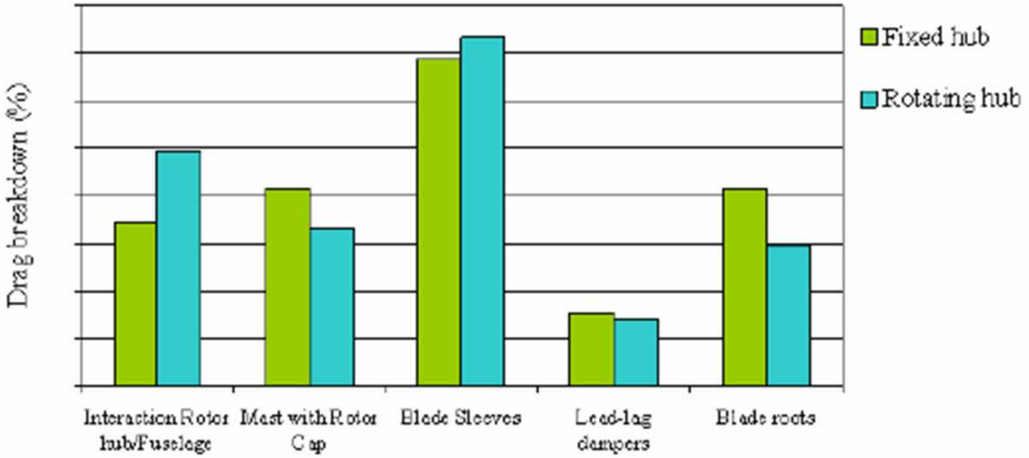


Results considered by Airbus
of utmost importance
for performance prediction
of the landing configurations

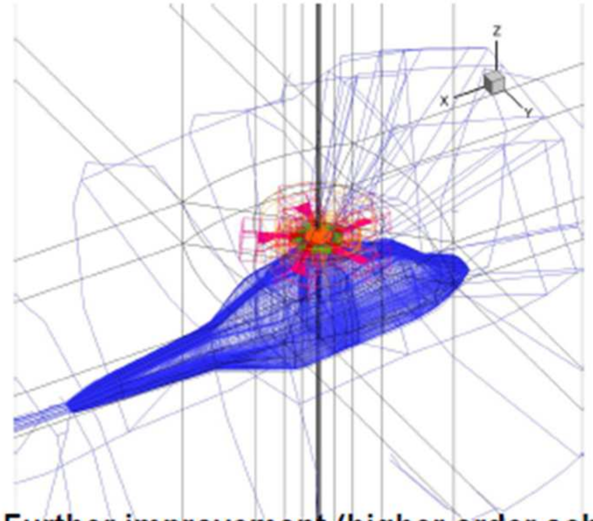
ONERA/DAAP computations

Helicopter results with elsA : rotor head with complete mechanism (courtesy of Airbus-Helicopter)

Drag breakdown of the rotor head

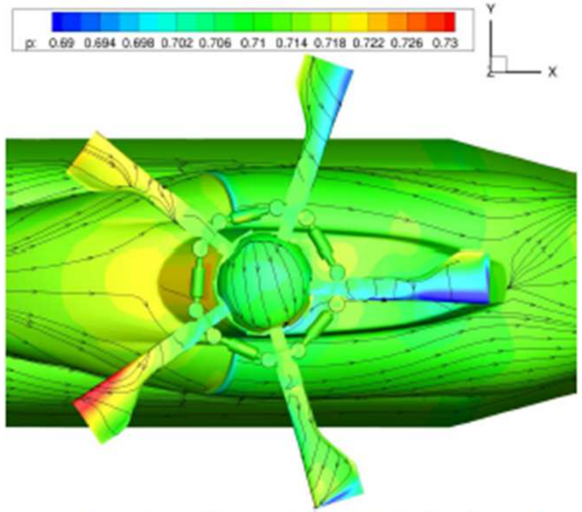


Tailshake phenomenon study : modal excitation of the structure of the rear parts by the wake of the upper parts



Unsteady *elsA* simulation
36 million points
85 processors
(k,ω + SST)

2nd order in space

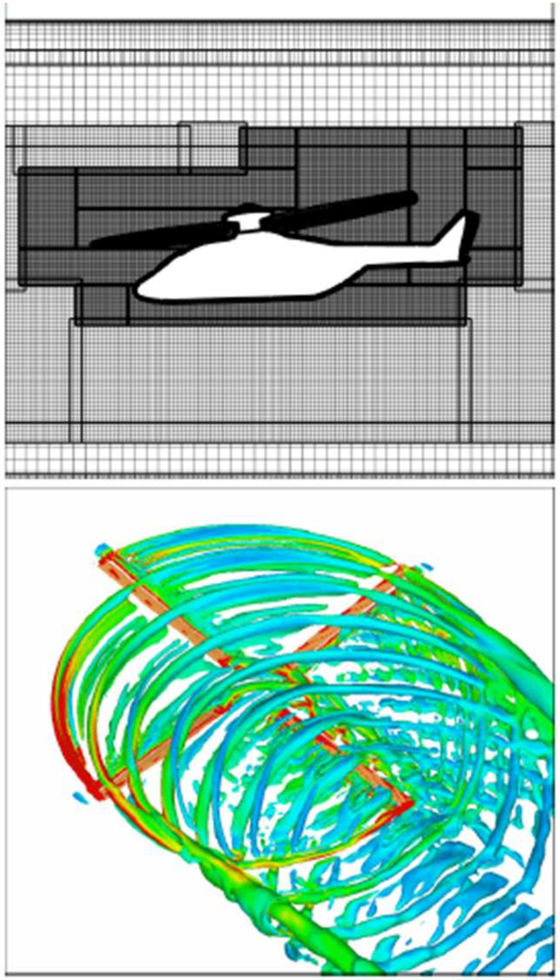


Further improvement (higher order schemes) necessary for a deeper understanding of the tailshake physics

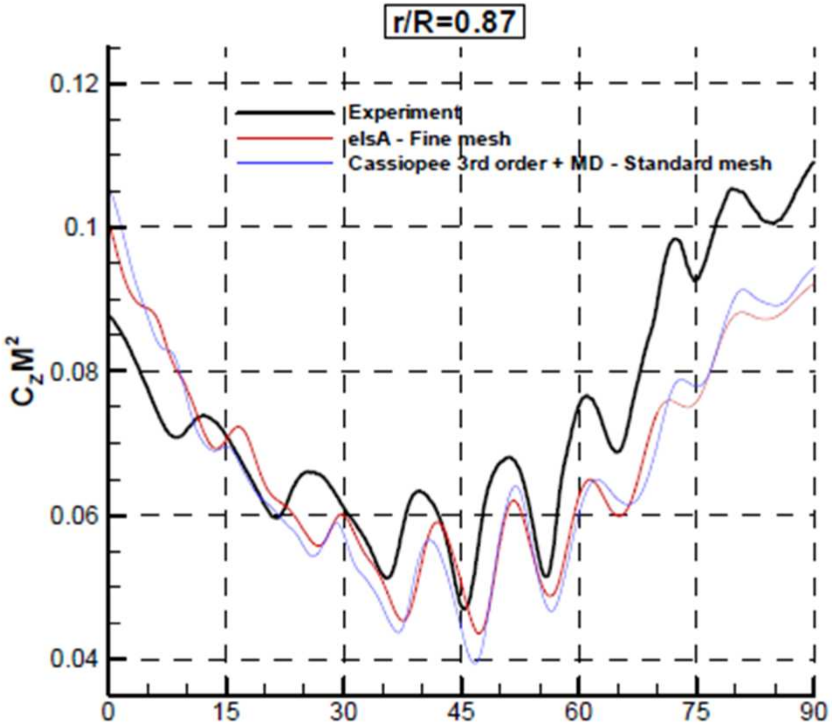
A brief outline of some elsA capabilities

- Chimera Method & CFD results with *elsA* and *Cassiopée*
- *Cassiopée* – Grid generation, Chimera techniques, Post-Processing
- Numerical simulations of technological effects in turbomachinery with Chimera techniques
- Specific numerical treatments for rotating machines (Turbomachines & CROR) in *elsA*
- Aeroelasticity capabilities in *elsA* software
- Aerodynamic Shape Optimization using *elsA* software
- Numerical schemes in *elsA* software - Towards high order accuracy
- Time Spectral Method for unsteady computations
- Turbulence & transition modelling in *elsA* software
- LES-DES capabilities in *elsA* software
- *elsA* & HPC

Mesh strategies (curvilinear / Cartesian mesh)
B105 helicopter rotor in descent flight – BVI noise



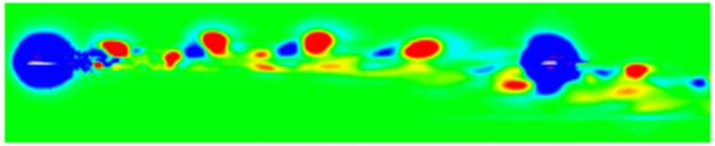
- Partitioning of domain (body grids/Cartesian grids)
- Automatic generation of Cartesian grids
- Automatic assembly and blanking



2D order scheme, Chimera computation, fine mesh : 28M pts

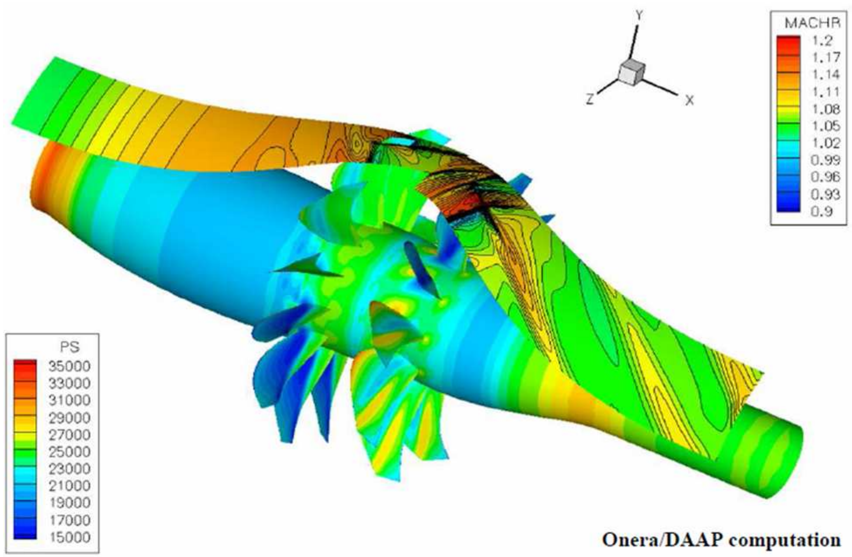
3D order cartesian scheme, Cartesian/Curvilinear mesh : 8M pts

Simulation carried out by T. Renaud (Onera)

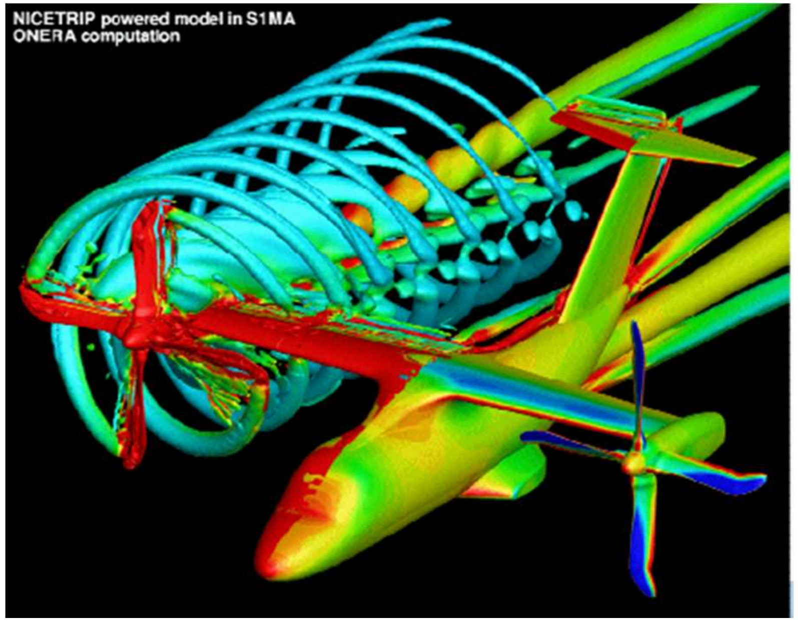


Reneaux, Beaumier, Girodroux-Lavigne
Advanced Aerodynamic Applications with the elsA software
Aerospace Lab, Issue 2, 2011

Rotating components with chimera technique



Example of CROR steady calculation



Tilt-rotor calculation (project NICETRIP)

ONERA/DAAP computations

ONERA
THE FRENCH AEROSPACE LAB

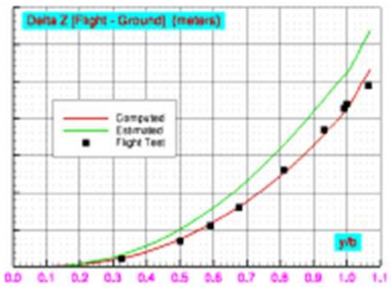
elsA Aeroelastic Simulations : Static coupling

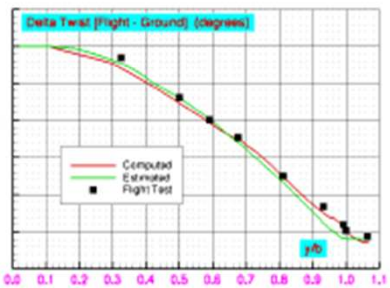
Objectives

- Flight shape deformation, control surface efficiencies

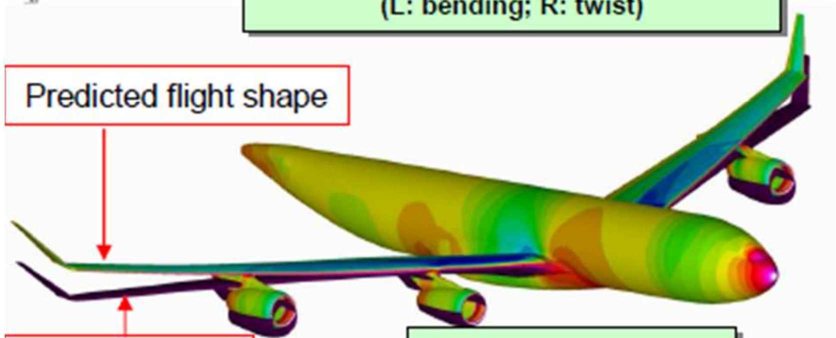
Projects

- French & EU programs



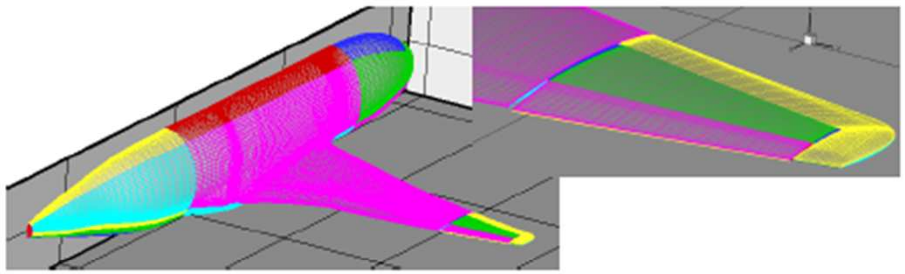


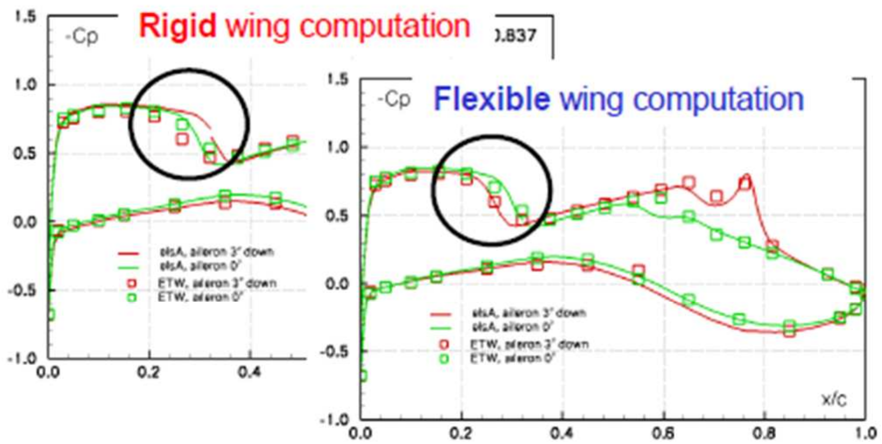
Simulation / Flight test Comparison (L: bending; R: twist)



Aircraft configuration (EU project)

wing-body model: aileron efficiency





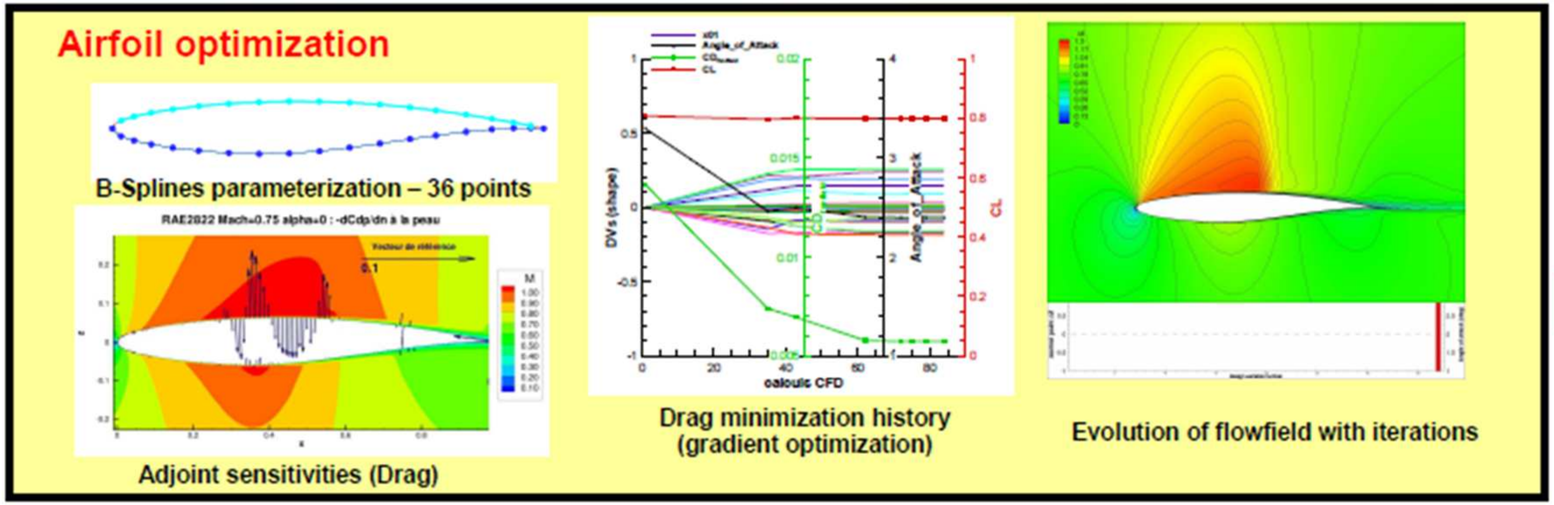
	C_Z δ=0°	C_Z δ=3°	$dC_Z/d\delta$
Experiment	*0.4869*	*0.4956*	*2.90 E-03*
Rigid wing	0.4646	0.4836	6.33 E-03
Flexible wing	0.4651	0.4751	3.33 E-03

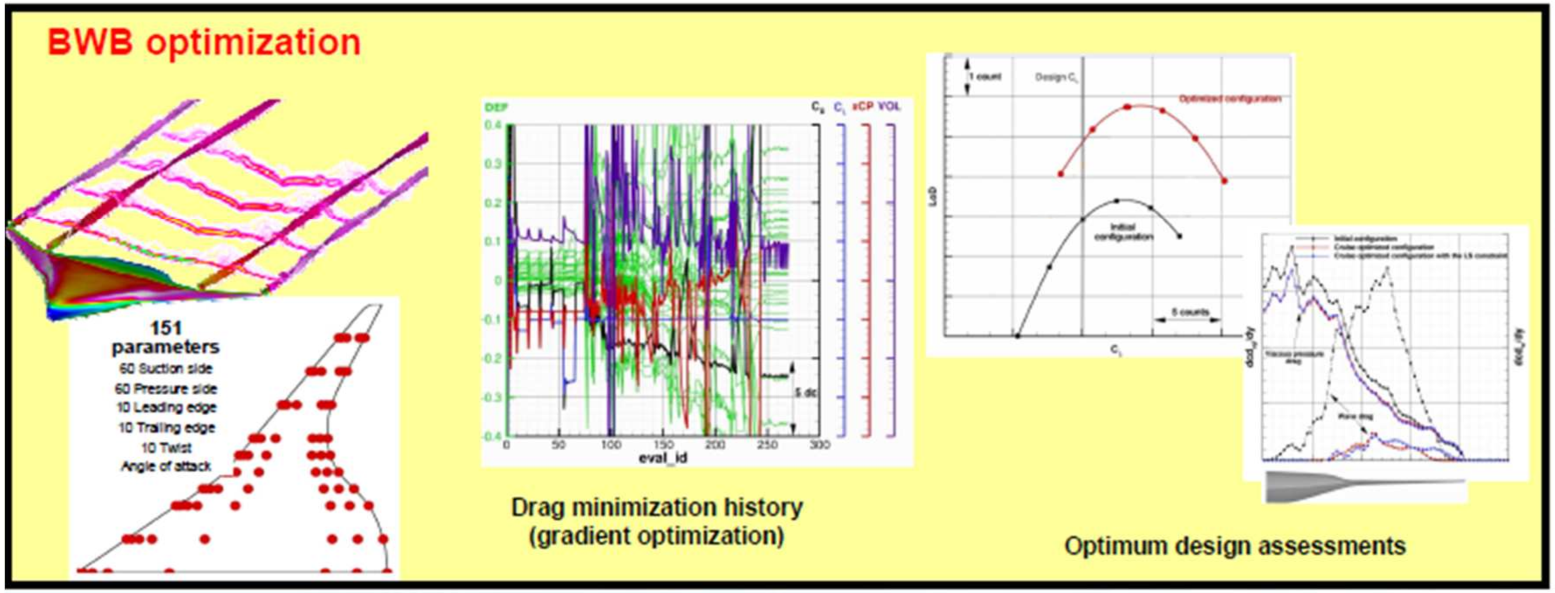
Err > 100% !

Err < 15 %

ONERA/DADS computations

Examples of adjoint-based Aerodynamic Optimization with elsA





From simple to complex applications …

ONERA/DSNA & ONERA/DADS computations

Main turbulence models in elsA

Main turbulence models in *elsA*

Eddy viscosity models

- k-ε (Jones-Launder, Launder-Sharma, Chien)
- k-ω (Wilcox, Menter BSL & SST, Kok) + buoyancy
- k-l (Smith)
- ν_t Spalart-Allmaras (also k-ν_t and curvature correction)
- k-kL (ONERA) + buoyancy

Algebraic Reynolds stress models

- ASM-ε Shi-Zhu-Lumley
- EARSM k-kL (ONERA) + curvature correction + EAHFM (thermal)
- EARSM k-ω Hellsten + EAHFM (thermal)

Reynolds stress models

- Speziale-Sarkar-Gatski (SSG) + ω Menter
- Other DRSM models + elliptic blending in development

Scale Adaptive Simulation

- Original version (Menter) + improved version (ONERA)

ZDES with elsA (1/2)

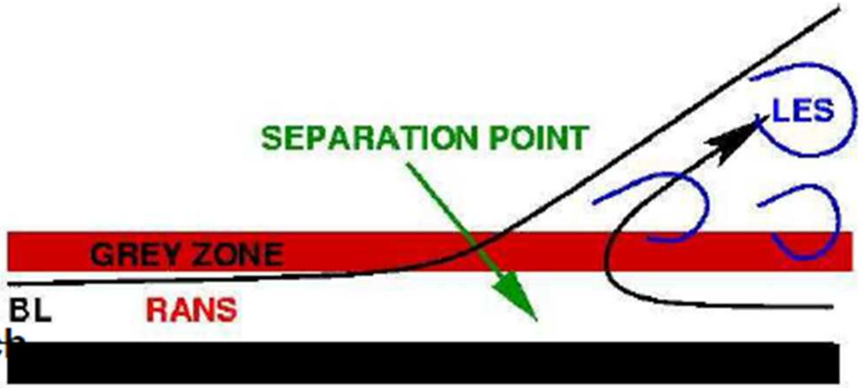
Objectives:

→ RANS for attached BL

→ LES into separation / complex interactions

« Philosophy »:

→ Determine block by block the model approach



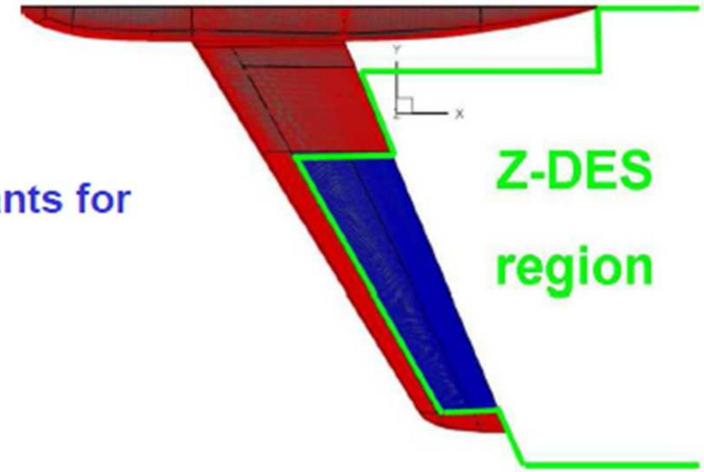
→ RANS – SA (1994) → attached BL

→ DES-1997 (Spalart)

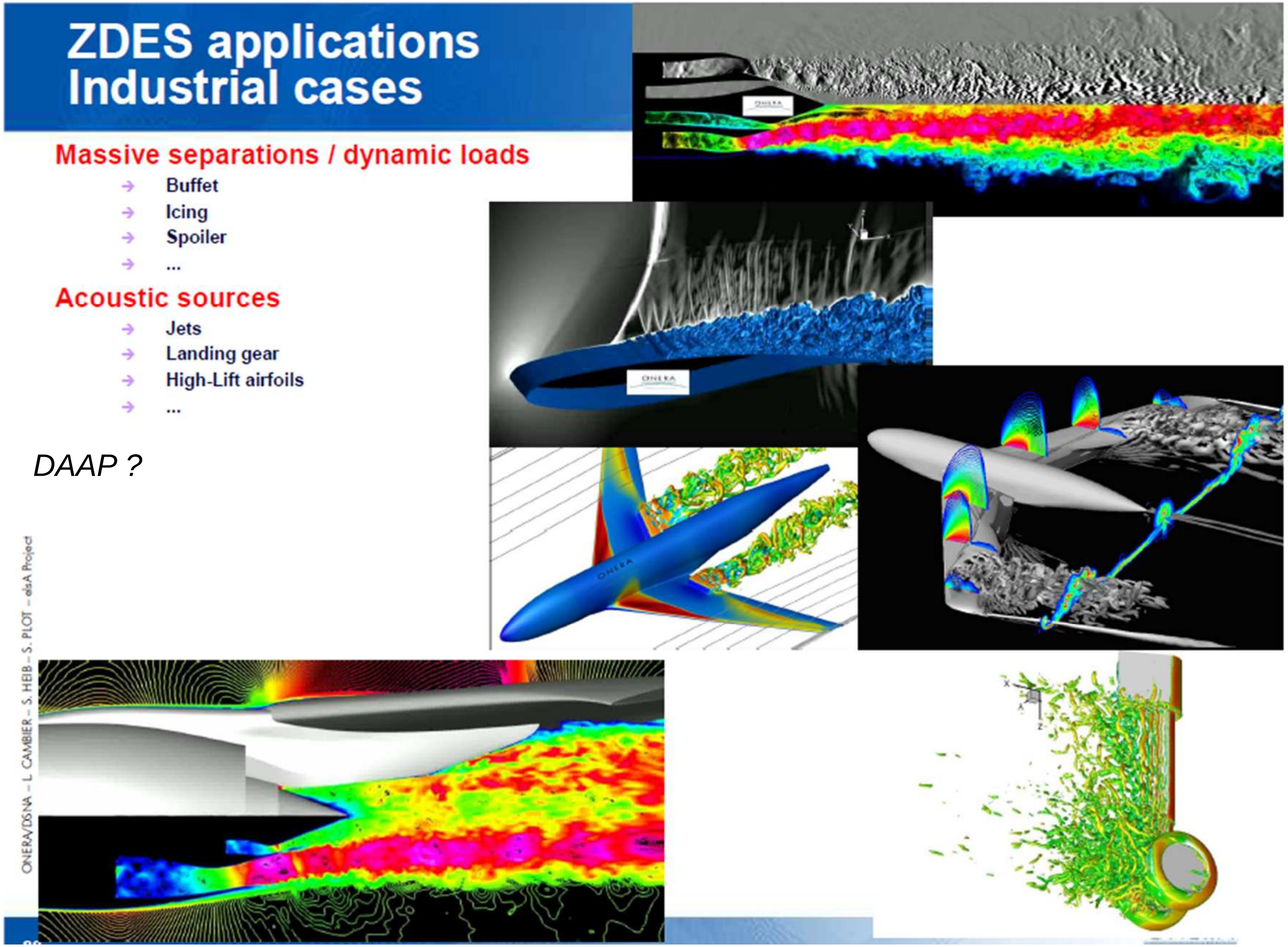
→ DDES (Spalart, Deck et al., 2005)

→ ZDES (Deck, 2005… 2011) with different variants for

$$\tilde{d} \equiv f\left(d, \Delta, \upsilon_t, U_{i,j}\right)$$



ZDES with elsA (2/2)



DAAP ?

ONERA/DSNA & ONERA/DADS computations

elsA software : RANS and transition

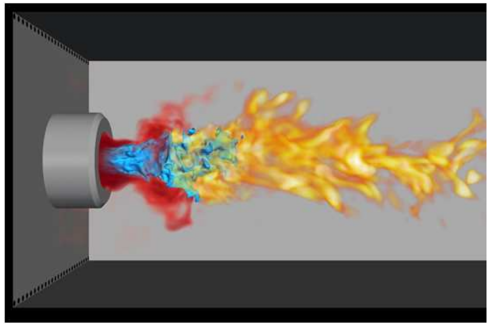
Methods in elsA

- Correlation based criteria
  - No compressibility effect, no crossflow (only longit. criteria)
- High fidelity transition criteria (based on stability theory)
- Other phenomenon :
  - Attachment line contamination (ALT)
  - Relaminarisation
  - Wall roughness

Futur developments

- Improvements concerning attachment line contamination and relaminarisation,
- Present γ-Re_θ model is Menter 2006, could be updated,
- Hypersonic flows above Mach 4 (second instability mode),
- Coupling to stability calculations, from low speed to equilibrium hypersonic flows.

CEDRE: presentation and examples



A. Murrone, N. Fdida, C. Le Touze, L. Vingert, Space Propulsion, 2014, Cologne

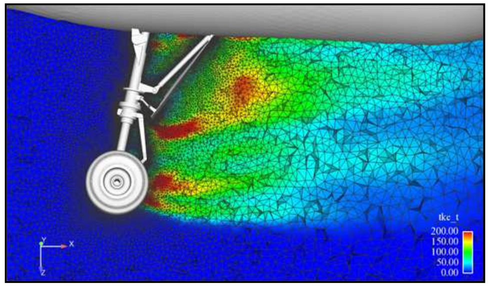
Reference code at ONERA for energetics and propulsion

Generalized unstructured grids (polyhedra)

- MUSCL, finite volumes
- Explicit or implicit time integration
- Up to fourth order

Parallel computations with good scalability (> 8000 cores)

- MPI, automatic partitioning and balancing
- Parallel I/O library



L. Sanders, N. Lupoglazoff, F. Vuillot, E. Manoha, D. Luquet, F. de la Puente, 19th Aeroacoustics Conference, 2013, Berlin

Gulfstream/Nasa PDCC nose landing gear (BANC workshop)

Multi-physics

Internal coupling (solvers dedicated to physical systems)

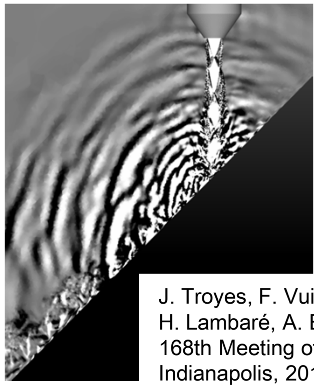
- **CHARME** : Navier-Stokes, multi-species, turbulent, reactive, real gases, multi-phases, all Mach, o(4)
- **SPIREE** : dispersed phases (Eulerian)
- **SPARTE** : dispersed phases (Lagrangian)
- **ACACIA** : thermal solution in solids
- **ASTRE** : radiation (Monte-Carlo)
- **REA** : radiation (discrete ordinates)
- **PEUL** : advanced chemistry
- **FILM** : liquid films

External coupling (CWIPI, OpenPalm)

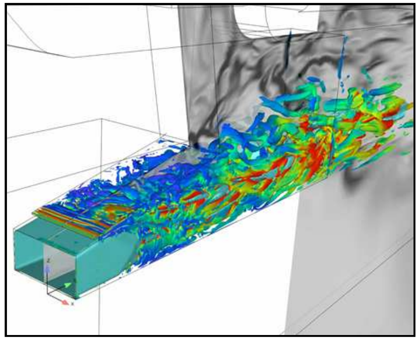
Moving/deforming grids (conservative ALE)

RANS, ZDES or LES modeling

Zonal approach (domain modeling)



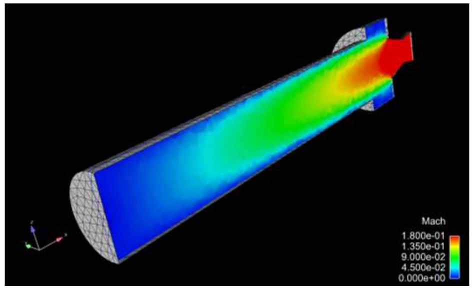
J. Troyes, F. Vuillot, H. Lambaré, A. Espinosa, 168th Meeting of the ASA, Indianapolis, 2014



B. Sainte-Rose, N. Bertier, S. Deck, F. Dupoirieux, Combustion and Flame 159 (2012), 2856-2871

CEDRE: additional examples

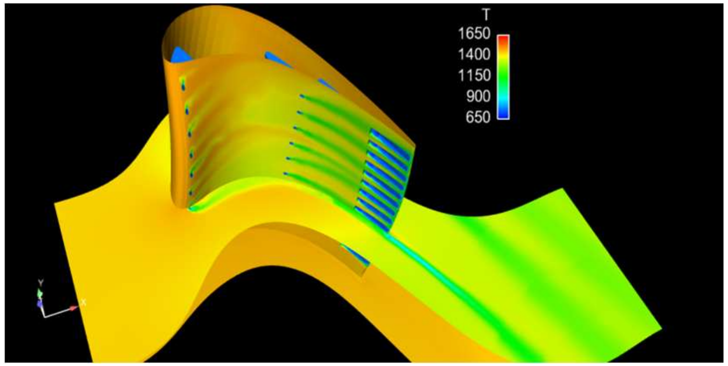
Surface regression in a model SRM (Solid Rocket Motor, PR CYPRES)

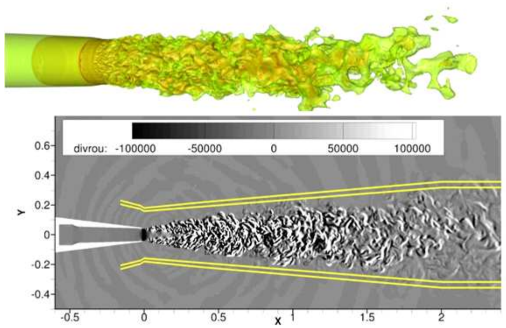


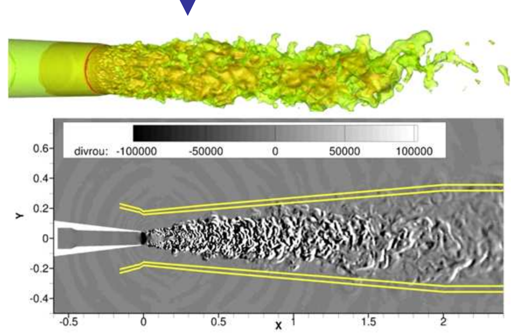
D. Gueyffier, F.X. Roux, Y. Fabignon, G. Chaineray, N. Lupoglazoff, F.Vuillot, F. Alauzet, *"High-order computation of burning propellant surface and simulation of fluid flow in solid rocket chamber"*, AIAA 2014-3612, AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 28-30, 2014, Cleveland

Some ongoing works

- Support to *elsA* for hybrid grids
  - Test case CM2012 cooled turbine blade
- CEDRE high order
  - Jet noise, Onera PHI80 nozzle (900K)
  - O2 on 55 Mcells (tetrahedra/prisms)
  - O4 on 17 Mcells (tetrahedra/prisms)







ONERA/DSNA & ONERA/DEFA computations

Composite mesh strategies for flexibility and accuracy
Hybrid, IBC, Cartesian (on-going work and near futur)

- **Hybrid stuctured/unstructured grid and solver**
  - Consolidation of numerical methods (gradients, scheme, implicit, unsteady, etc ...) for complex applications

- **Immersed Boundary Condition - IBC**
  - Implementation of accurate formulation o(h) of the wall position thanks to a dynamic coupling between *elsA*-Connector (**Cassiopee**),
  - Towards the body movements :
    - With simple formulation o(1),
    - Wall distance recomputation with “level set” approach.

- **Cartesian**
  - Implementation of Cartesian formulation of usual scheme

elsA-H – Context and motivation (1/2)

Why elsA-H ?

- *elsA* : industrial solver for multiblock structured grids : performant, accurate ; other capabilities : overlapping, chimera methods, nearmatch connectivity ; modules for aeroelasticity and for optimization design
- *Some* limitations due to grid generation for (very) complex configurations, technologic effects
- Keep as much as possible the best of MBS (efficiency, accuracy in BL) and of unstructured (mesh generation, local adaptation) in a single environment efficient in parallel

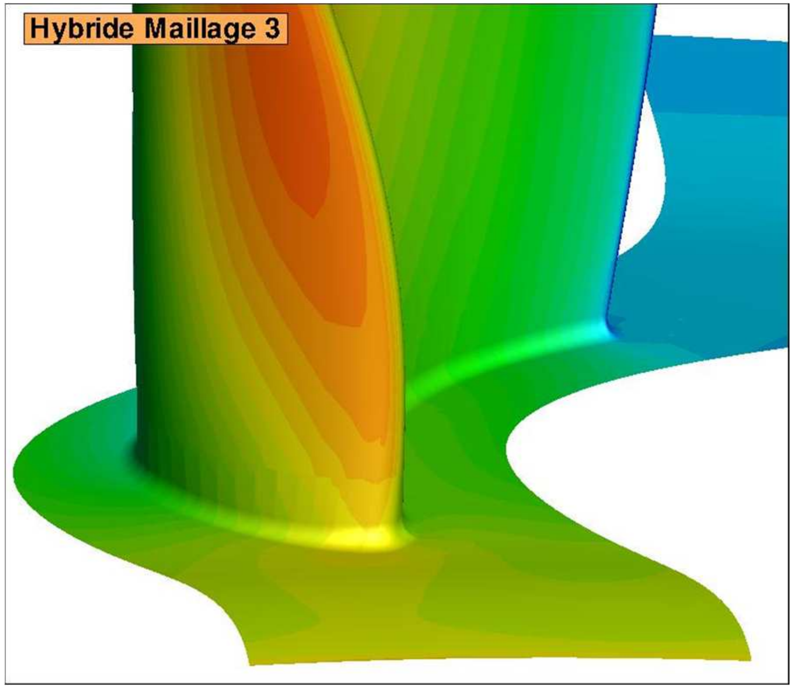
How ?

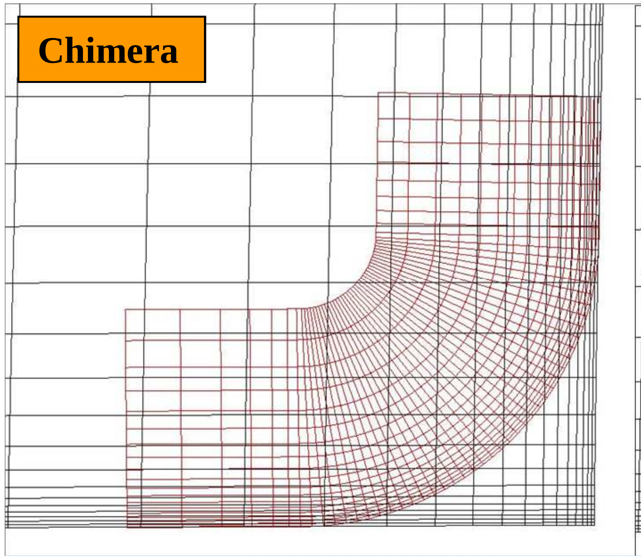
- *elsA* extension to unstructured grids ;
- all structured capabilities are kept without degradations ;
- C++ classes added for unstructured grids ;
- When possible, use of algorithms existing for structured grids.

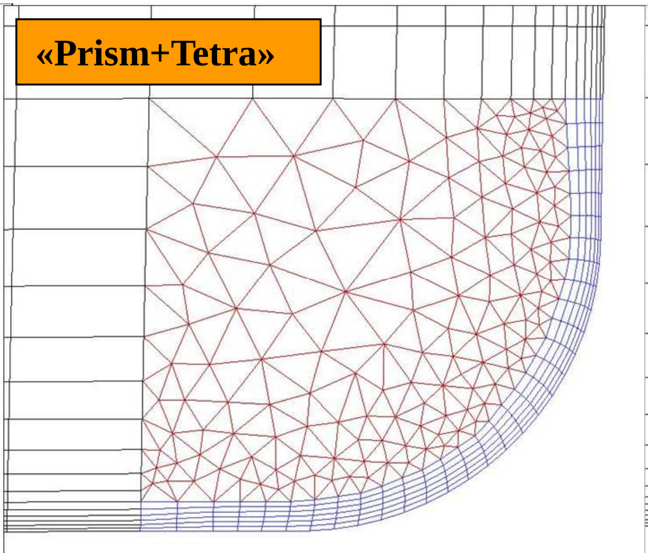
Hybrid mesh : Example of application: blade fillet modeling

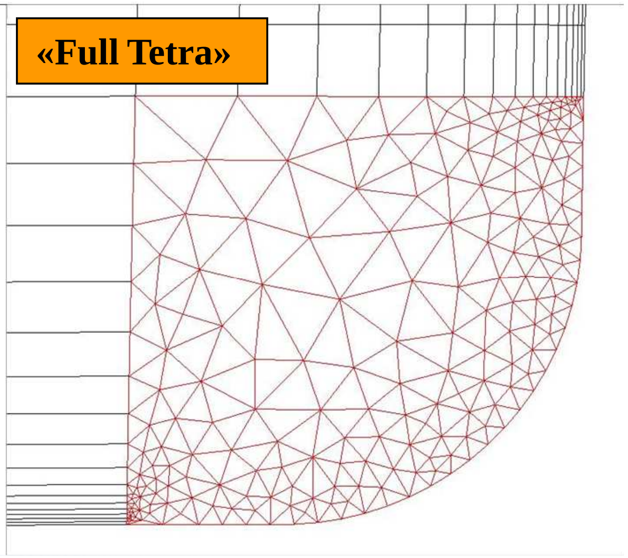
- Industrial 3D turbine rotor
- Blade fillet radius = 1 mm
- Comparison Hybrid vs Chimera
- Different hybrid strategies tested
  (with or without prismatic elements)

Lionel Castillon, Marie-Claire Le Pape
ONERA/DAAP & ONERA/DSNA computations



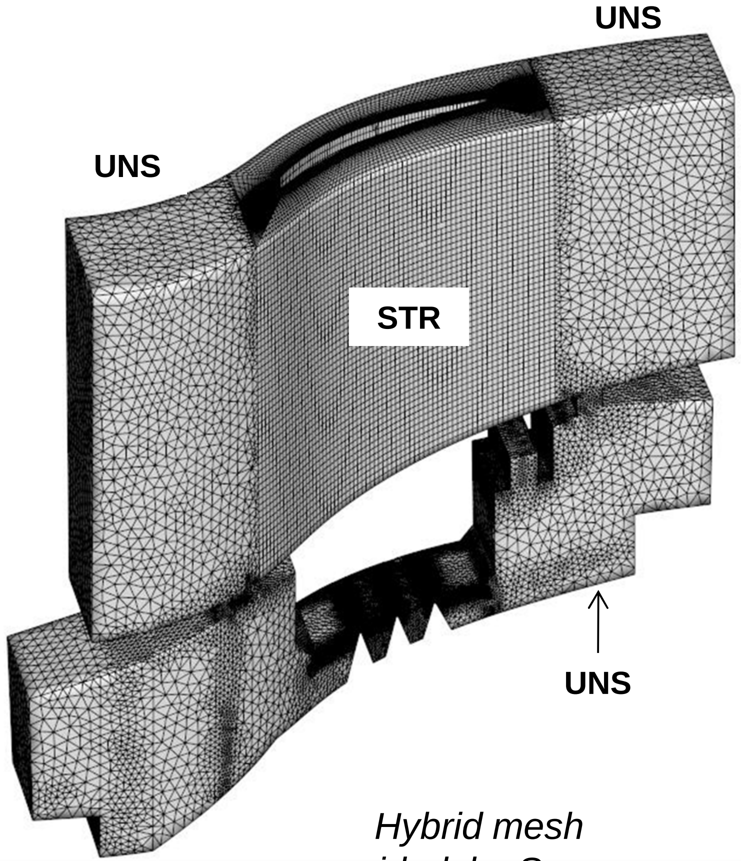




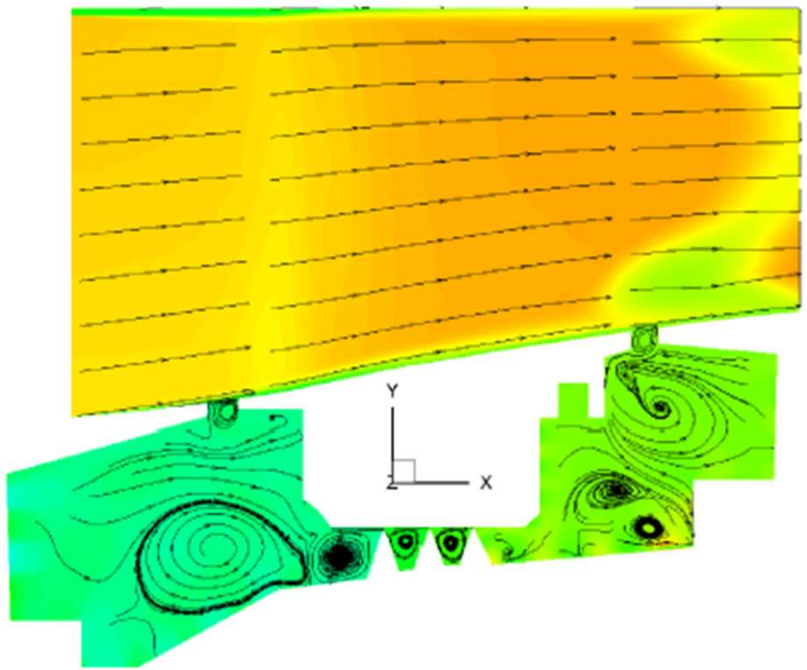


elsA-H : Hybrid simulations with 2nd order FV STR/UNS solver (1/2)

3D HYBRID: RANS, 2^{nd}-ORDER



Hybrid mesh provided by Snecma



Pressure field in the inter-blade passage and in the cavity

Marta de le Llave et al., "Further developments in the multi-block hybrid CFD solver elsA-H, AIAA 2012-1112

elsA-H : Hybrid simulations with 2nd order FV STR/UNS solver (2/2)

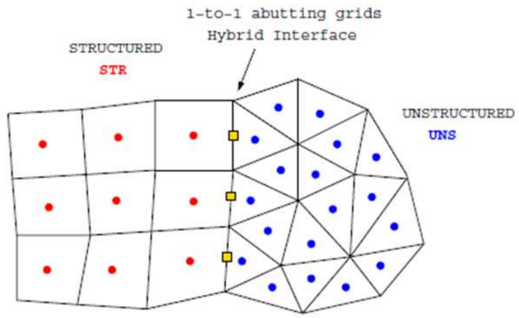
Generalised multi-zone interfaces:

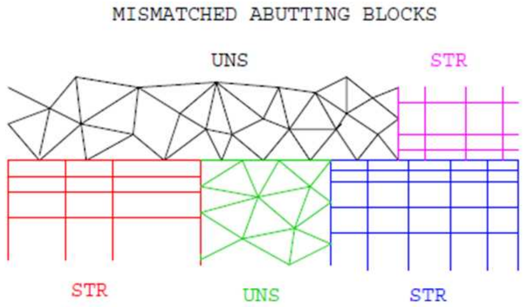
- Structured/Structured (elsA, elsA-H)
- Unstructured/Unstructured (elsA-H)
- Structured/Unstructured (elsA-H)

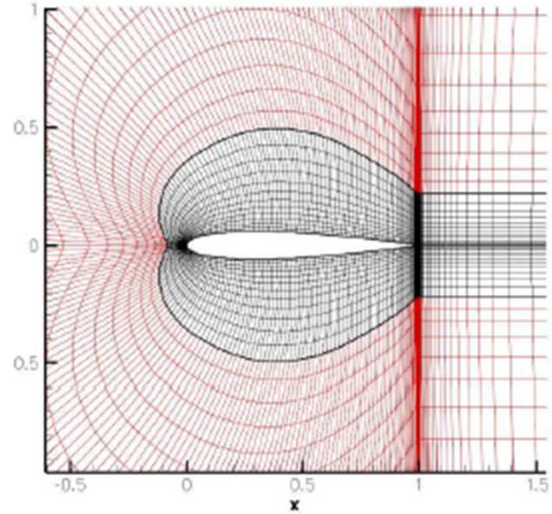
Parallel multi-block capabilities:

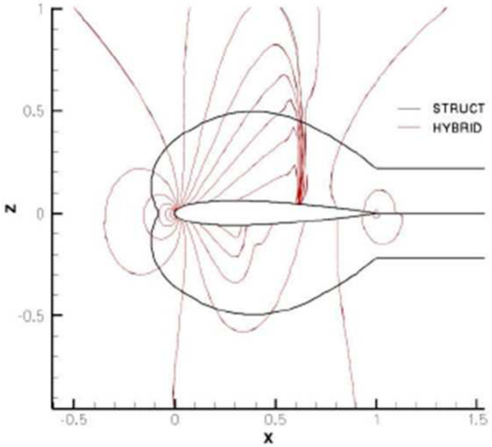
- 1-to-1 Matching blocks
- Mismatched abutting blocks

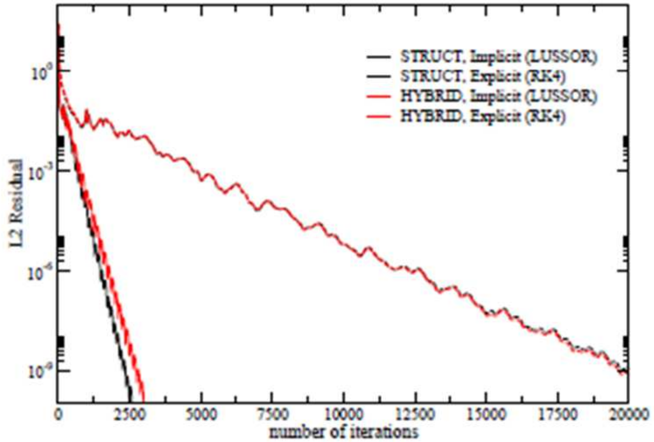
Claude Marmignon et al., “Development of an agglomeration multigrid technique in the hybrid solver elsA-H”, ICCFD7-1603











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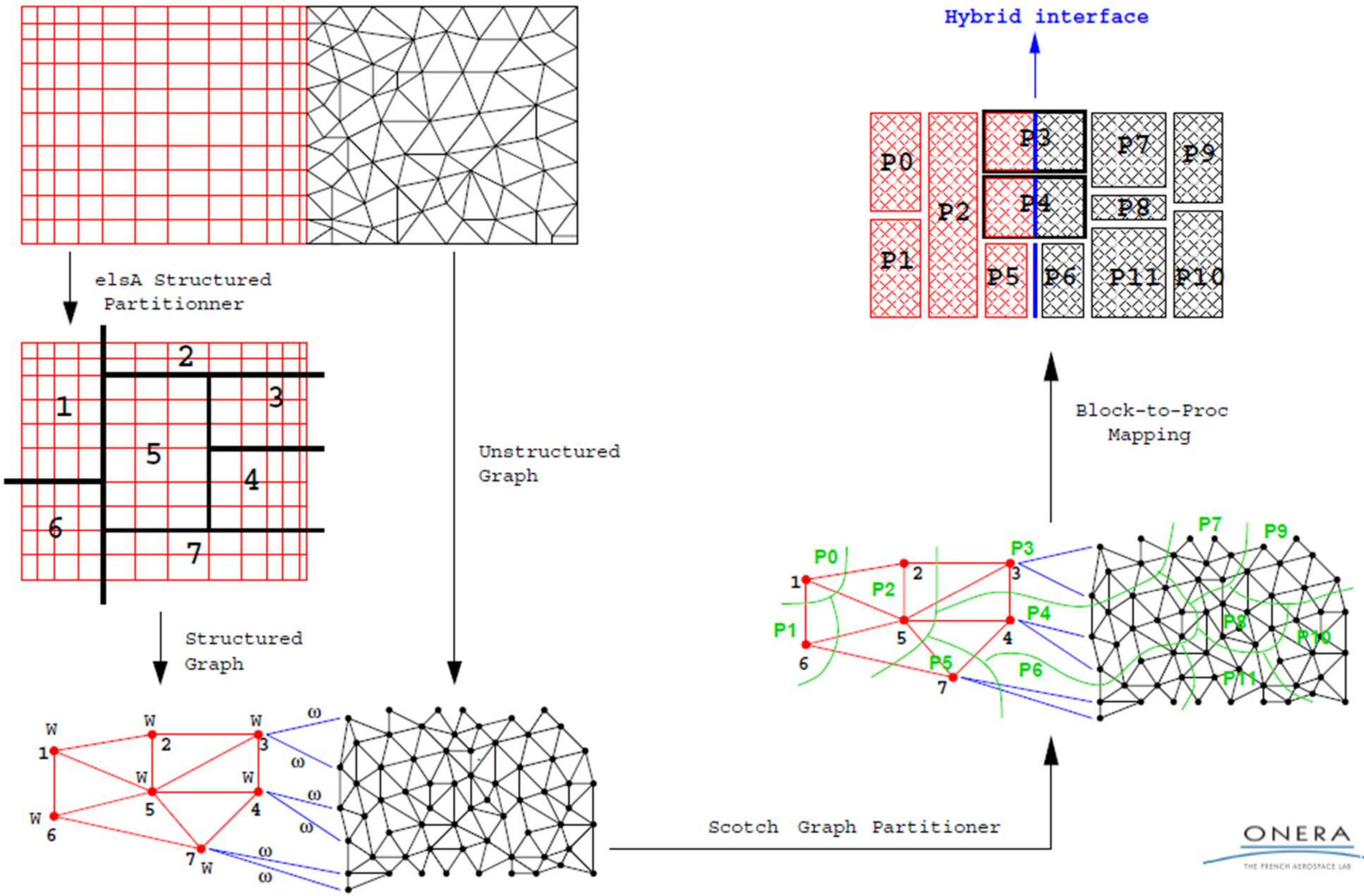
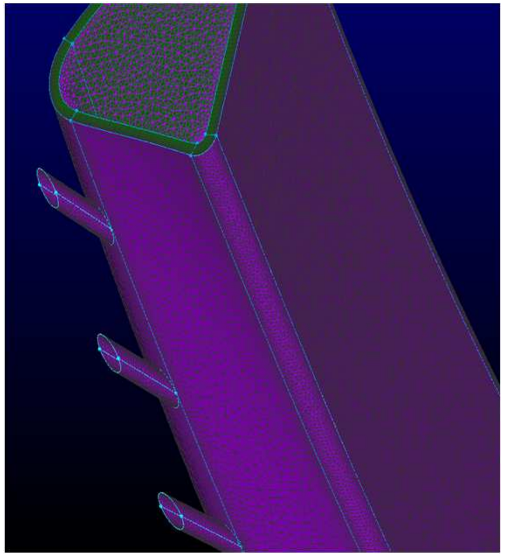
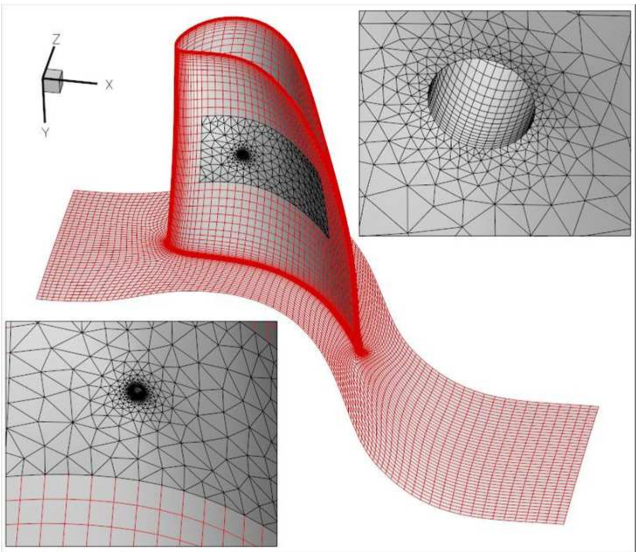
Hybrid Mesh strategy : Domain decomposition for parallel

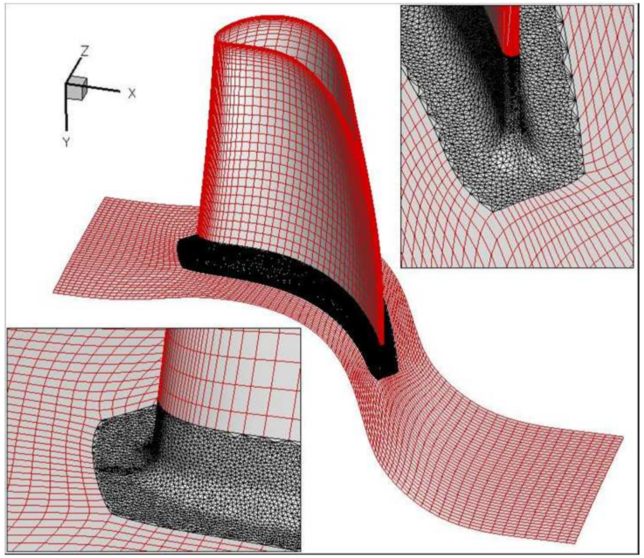


Hybrid grid strategy and pre-processing tools

- 2 grids performed separately with coincident matching
  - *Multi-block structured* meshing tool : blade and channel (structured part)
  - *Unstructured meshing tool* : technological effect (non structured part)
- Creation of CGNS input file for *elsA*-Hybrid:
  - CGNS structured part prepared with in-house turbomachinery tool *Archibald*
  - CGNS non structured tree from *Pointwise*
  - Use of the tools *Fetch* (grid indexing) et *Gentiane* (matching between structured/non structured parts) in order to merge the 2 CGNS trees
- **Action under way : Interaction with mesh generation teams in order to get a hybrid mesh generation tool in a single environment (IJK structured + unstructured)**



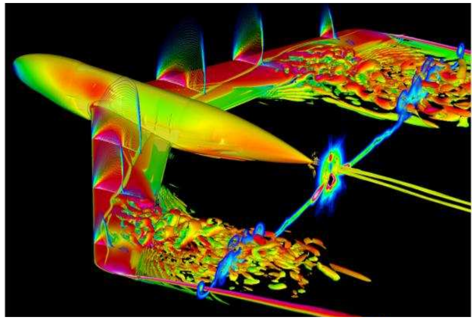




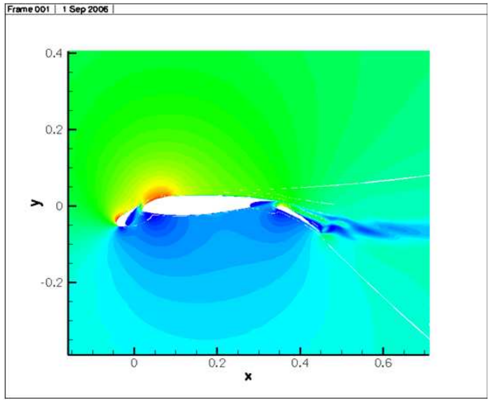
CFD State of the art and challenges - Some elements

<u>Progresses : « RANS Second order type » CFD mature but</u>

- RANS model limited to « nominal » flow configurations
- Mesh convergence analysis show the limitations of classical 2nd order methods regarding the current mesh used (regularity, resolution, etc…)
- Boundary condition treatment for sensitive configurations
- Uncertainty propagation and identification of domain of validation
- Unsteady computations required for flow sensitive configuration



elsA DES computation ONERA/DAAP



Unsteady high-lift computation ONERA/DSNA

<u>Challenges : (High) Fidelity In CFD methods requires firstly ***accuracy***</u> for advance turbulent flow simulations (LES, DES, DNS)

- Development of higher order methods : DG, RDS, RBC, ENO, …
- Need of higher order meshes, hybrid polyhedral meshes,…
- Feasibility :
- ***Robustness*** in order to demonstrate the interest (mesh or DoF convergence improvement)
- ***Efficiency*** in order to make them applicable to industrial type configurations
    - Implicit, H/P multigrid, parallel advanced architecture, new processor (GPU)
    - New software architecture for dynamic adaptation and composite mesh management
    - Adaptation : H (mesh), P (shape functions), M (modeling)
    - Application to complex unsteady flow simulation : huge data management

Context: Simulation & HPC

Internal users expectations, as front end to the external users :

New class of methods to develop better models of flow behavior

➔*confidence that novel numerical schemes will better preserve their models from spoiling by numerical diffusion/dispersion (still not a consensus),*

➔*more efficiency : accuracy versus number of cells, grid convergence*

➔Objective : Billion cells, long unsteady runs, deforming & overlapping meshes (LES, DES, Aeracoustics)

Evidences :

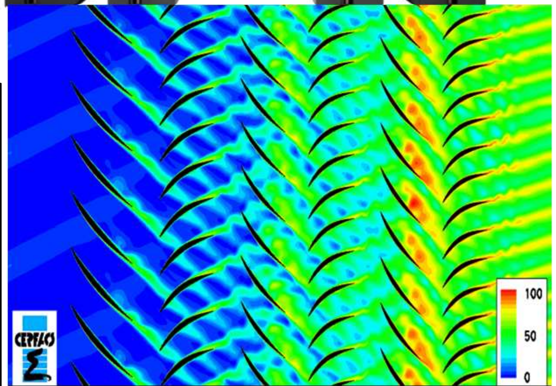
1/ Ongoing heavy development plans of the legacy software to develop & validate new functionalities ➔*risks on the scalability towards Petaflop's computing*

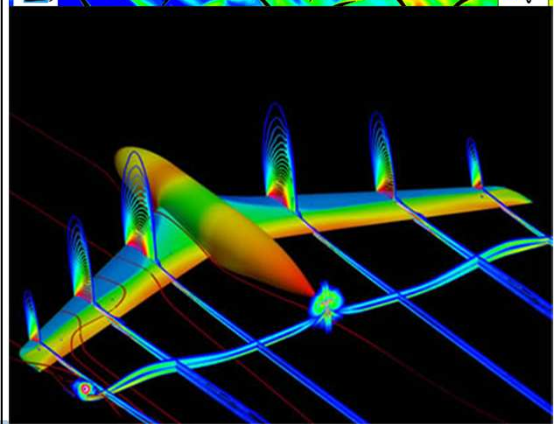
2/ Innovative research at Onera : numerous prototypes

- Grid strategies : - structured
  - unstructured
  - overset, self generated, adaptive

associated to model certification, international benchmarks

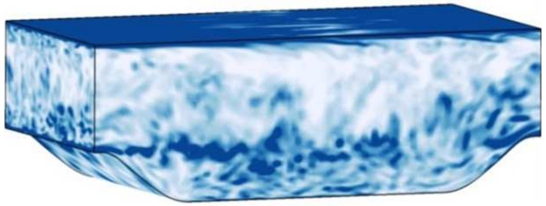
- Numerical schemes and non-linear solvers : DGM (h-p-M adaptation), VMS turbulence (Variational multiscale with hierarchy in basis functions), High Order FV
- Mesh/model/physics coupling strategies





AGHORA – High Accuracy Navier-Stokes Software Prototype for HPC

Scientific challenge : *High accuracy and efficiency for complex turbulent flow simulations with Navier-Stokes on HPC plate-formes*



Aghora – Periodic hill
DNS computation (DG O4)

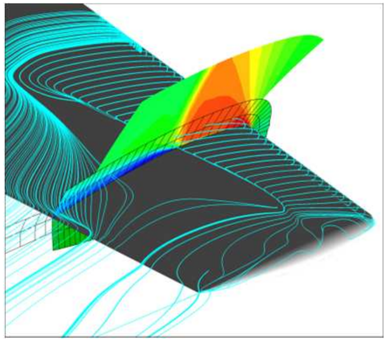
Aghora software prototype: CFD 2020

- *TRL 3 in 2015 for internal and external aerodynamics (Safran, Airbus)*
- Adaptative models : high-order schemes and meshes, multi-level models
- Efficient HPC programming on heterogeneous architectures (with Inria)
- Management of operational uncertainties (stochastic methods)

Physical modeling and numerics

- DG modal or nodal approach on unstructured polyhedra
- RDS development under way (with Univ. of Zürich)
- Internal and external flow configurations
- Different levels of turbulence modeling : RANS, DES, LES, DNS

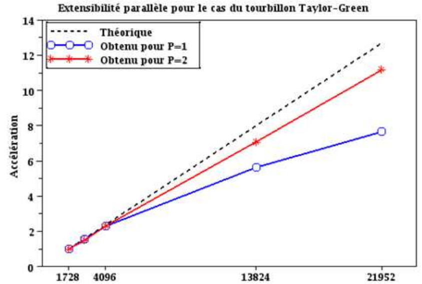
V. Couaillier, F. Renac, M.de la Llave Plata,,J.B. Chapelier, E. Martin, M.C. Le Pape "Turbulent Flow Simulations with the High-Order DG Solver Aghora", AIAA -2015-0058



Aghora – Onera-M6 wing
Transonic RANS $k\omega$ computation

Exemple of targeted application for 2020 : multi-stage axial compressor With LES using massively parallel architecture (with or without wall law)

Associated projects : PRF Aghora (Onera projects), European projects IDIHOM, ANADE, Possible new H2020 European project TILDA, French project DGCIS /ELCI, FP7 UMRIDA, High-Order CFD workshop on various Navier-Stokes test cases



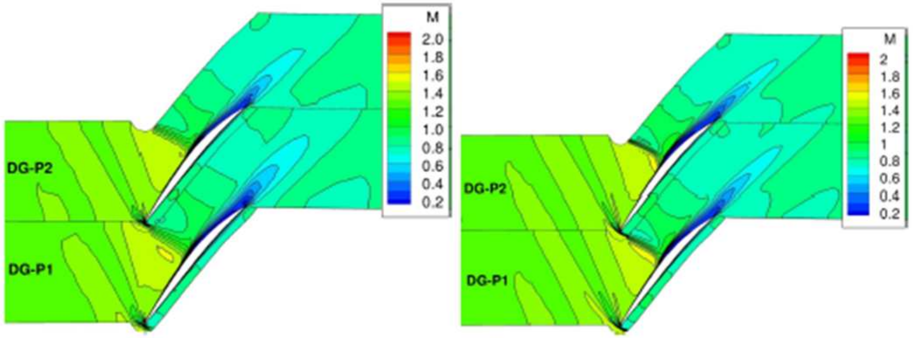
Aghora – Better strong scalability
with high polynomial degree

Aghora roadmap 2016-2020 :

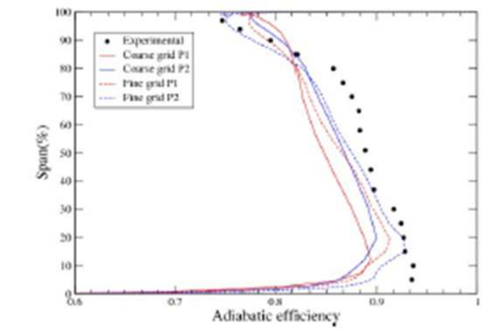
Further development and validations of Aghora for complex flow models and multi-physics (real gas effects and multi-physics + LES (TRL 6 in 2020)

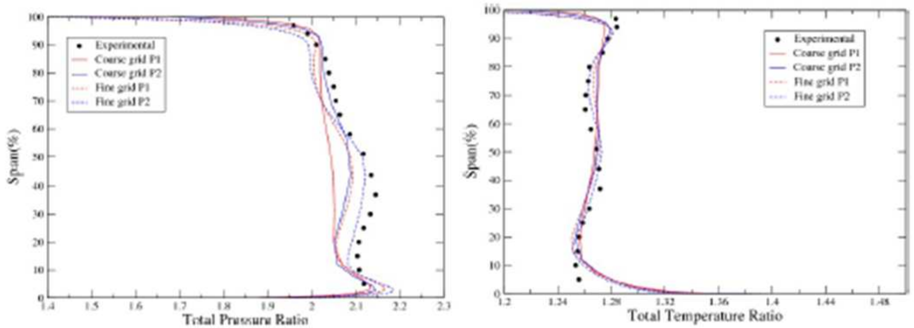
DG-p1/p2 simulations on hexahedral meshes

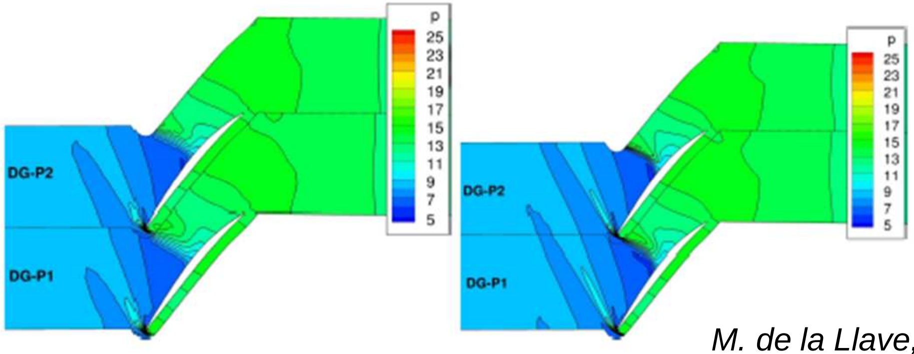
Coarse mesh with 87,769 points, fine mesh with 672,896 points.



Iso-contours of the Mach number (left: coarse, right: fine).







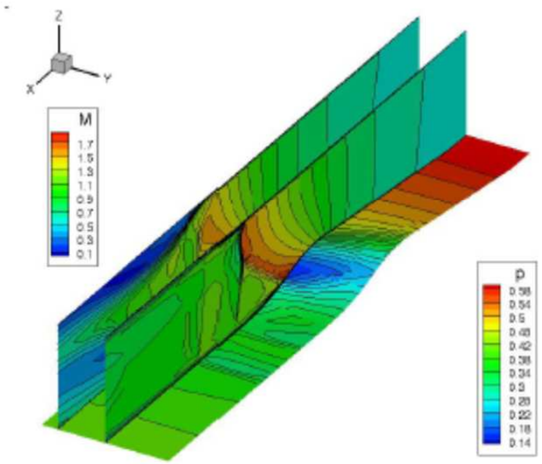
Iso-contours of the static pressure (left: coarse, right: fine).

Spanwise profiles of adiabatic efficiency, total pressure ratio and total temperature ratio.

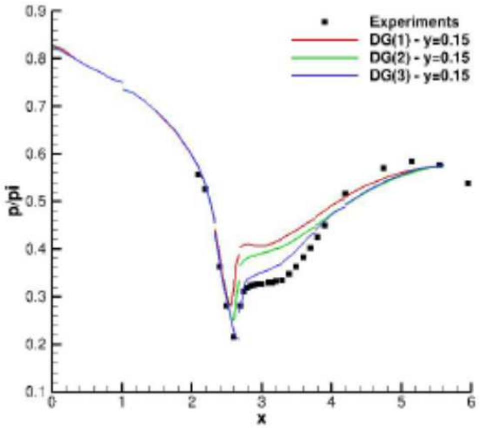
M. de la Llave,3rd International workshop on High-Order methods CFD methods, Kissimmee, January 2015

ONERA Aghora.

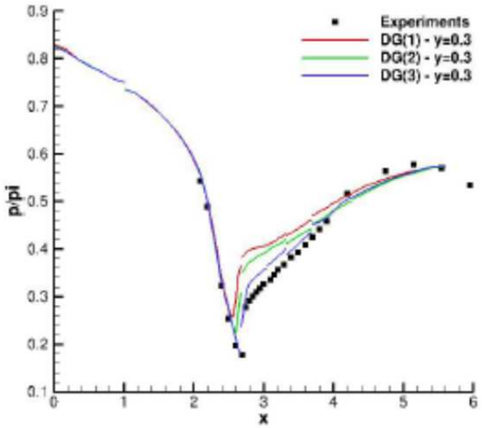
Wall pressure distributions



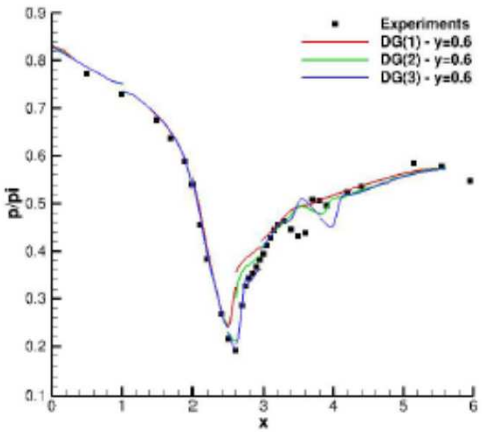
(a) DG(3)



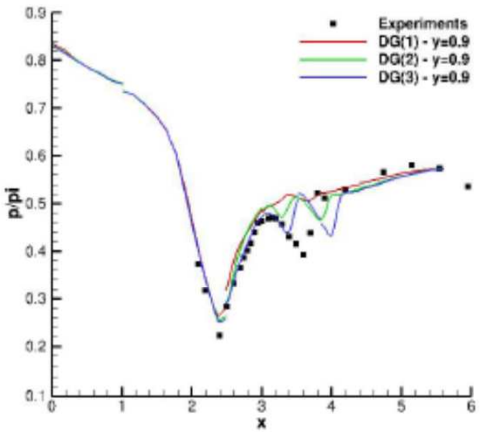
(b) $y = 0.15$



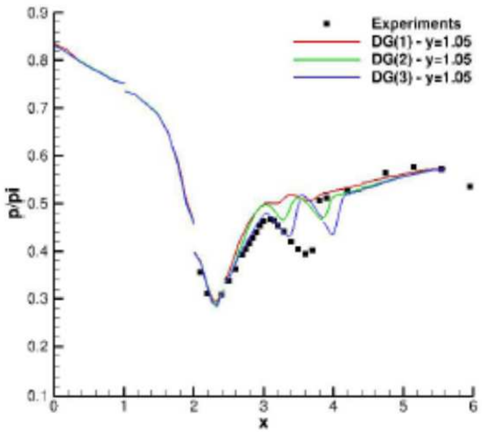
(c) $y = 0.30$



(d) $y = 0.60$



(e) $y = 0.90$



(f) $y = 1.05$

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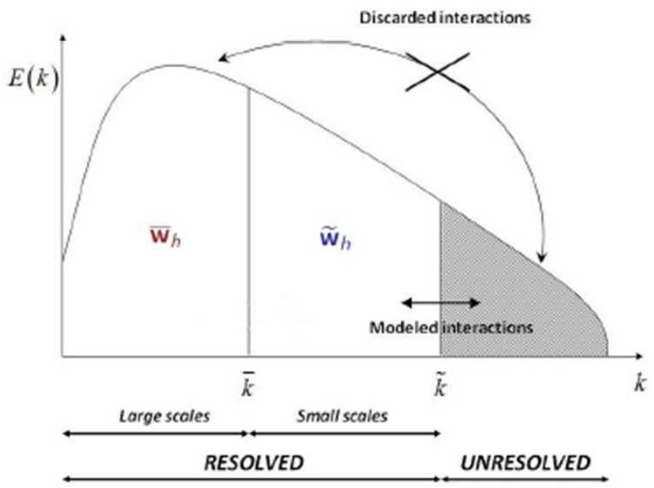
F. Renac,3rd International workshop on High-Order methods CFD methods, Kissimmee, January 2015

VMS approach



$$\bar{u} = \sum_{n=1}^{N} \sum_{k=0}^{\bar{p}} \bar{U}_n^k \bar{\phi}_n^k(x) \qquad \bar{\phi}_n^k \in \mathcal{V}^{\bar{p}}$$

$$\tilde{u} = \sum_{n=1}^{N} \sum_{k=\bar{p}+1}^{\tilde{p}} \tilde{U}_n^k \tilde{\phi}_n^k(x) \qquad \tilde{\phi}_n^k \in \mathcal{V}^{\tilde{p}}$$

$$\hat{u} = \sum_{n=1}^{N} \sum_{k=\tilde{p}+1}^{p} \widehat{U}_n^k \widehat{\phi}_n^k(x) \qquad \widehat{\phi}_n^k \in \mathcal{V}^{p}$$

$$\mathcal{NS}\left(\bar{\phi}, \bar{u} + \tilde{u}\right) = 0$$

$$\mathcal{NS}\left(\tilde{\phi}, \bar{u} + \tilde{u}\right) = \mathcal{M}\left(\tilde{\phi}, \bar{u}, \tilde{u}\right)$$

$$\mathcal{M}\left(\tilde{\phi}, \bar{u}, \tilde{u}\right) = \left(\tilde{\phi}, 2\nu_t \tilde{S}_{ij}\right)_\Omega \quad , \quad \nu_t = (C_s\tilde{\Delta})^2 |\tilde{S}(\mathbf{x}, t)| \quad , \quad |\tilde{S}(\mathbf{x}, t)| = \sqrt{2\tilde{S}_{ij}\tilde{S}_{ij}}$$

Residual-based VMS approach

- Separation of scales : $u = \bar{u} + u' \rightarrow \mathcal{L}u = \mathcal{L}(\bar{u} + u') = f$
- Large scales ($\bar{u}$) represented by the numerical solution
- Unresolved scales ($u' = \tilde{u} + \hat{u}$) modelled by $u' \approx \tilde{u} = \tau(f - \mathcal{L}\bar{u})$

LES computations using Aghora : Taylor Green Vortex at $Re = 3000$

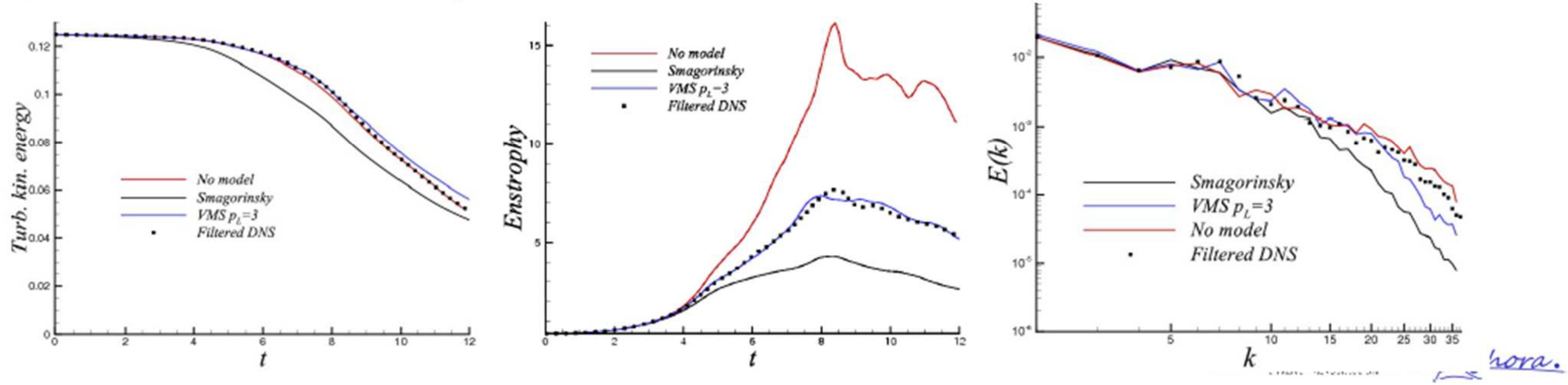
Approach	Order (p+1)	# Elts.	#Integration points
DG VMS	6	12^3	5.9×10^5
DG Smagorinsky	6	12^3	5.9×10^5
DG No model	6	12^3	5.9×10^5
DNS Reference	-	-	1.9×10^8

$$\boxed{\frac{\#\text{DoFs DNS}}{\#\text{DoFs LES}} \approx 320}$$

J.B. Chapelier et al., PhD Thesis, December 2013

Turbulent kinetic energy Enstrophy Spectra at enstrophy peak

Chapelier JB, de la Llave Plata M, Renac F, Lamballais E. Evaluation of a high-order discontinuous Galerkin method for the DNS of turbulent flows. *Comp. Fluids*. 2014;95:206-226.

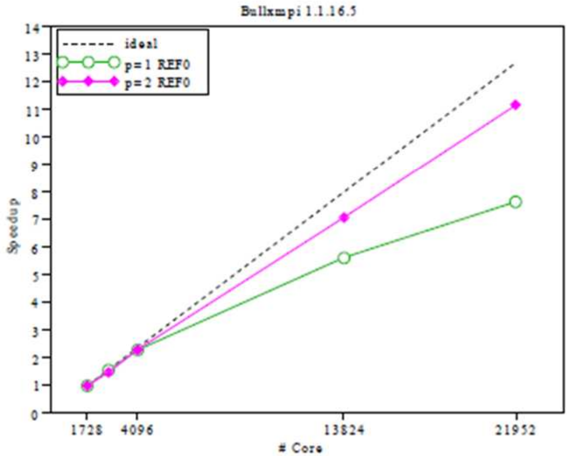


Aghora code :

Strong scalability tests

Numerical experiments using the Taylor-Green vortex

- Sensitivity of the polynomial degree p on the speedup with REF0 version on *Curie*
  - Strong scalability analysis on a mesh with 336 elements
    - Ratio elts/ghosts per domain ~ 4 at the largest scale
  - Receive-send message frequency (measured with 13 824 cores)
    - $p = 1$, $\sim$ 41 messages/s
    - $p = 2$, $\sim$ 15 messages/s
    - $p = 4$, $\sim$ 02 messages/s
  - On 21 952 cores with $p = 2$, efficiency of the speedup $\sim$ 88%



Strong scalability analysis

E. Martin, in
V. Couaillier, F. Renac, M.de la Llave Plata, J.B. Chapelier, E. Martin, M.C. Le Pape
"Turbulent Flow Simulations with the High-Order DG Solver Aghora", AIAA -2015-0058

NXO : High order FV method on arbitrary grids

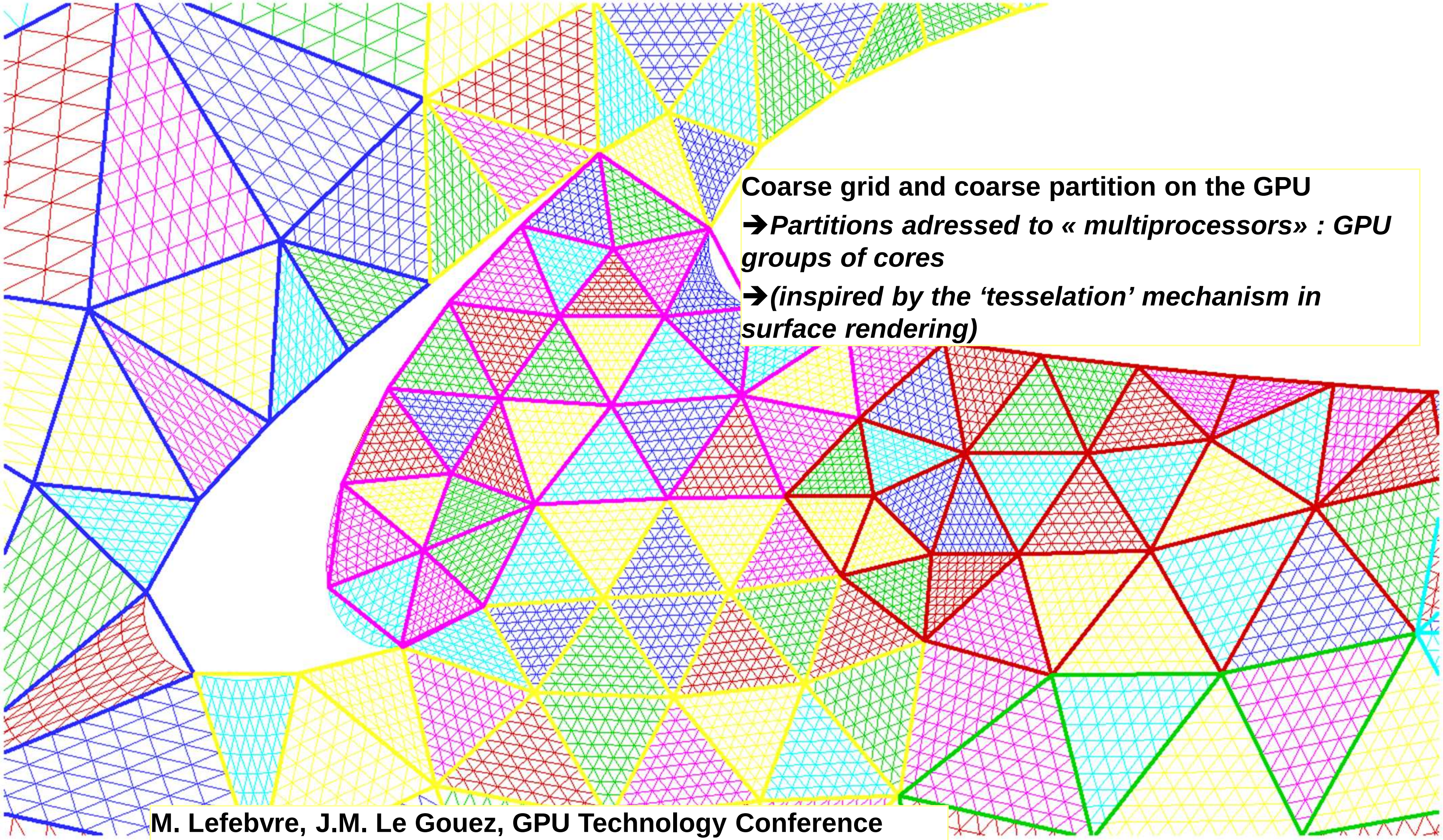
- 1 dof per cell and per equation, non compact spatial scheme
- Reconstructed polynomial variation of conservative variables by Weighted Least - Squares
- Unlimited projection of the polynomial variations on the cell interfaces :Interpolation from cell averages to interface averages

- On-going work to extend the procedure to high order geometry (cells and interface moments by curvilinear integrals)

- GPU version using a generic refinement on the multiprocessors of a coarse high-order grid

- Participation to the 3 High-Order CFD Workshops on 5 test-cases

GPU prototype for a HO Finite Volume method : a winning experience based on a hierarchical model (generic refinement on GPU of a coarse high-order grid on the CPU)



Coarse grid and coarse partition on the GPU

➔*Partitions adressed to « multiprocessors» : GPU groups of cores*

➔*(inspired by the 'tesselation' mechanism in surface rendering)*

M. Lefebvre, J.M. Le Gouez, GPU Technology Conference March 2013 San José

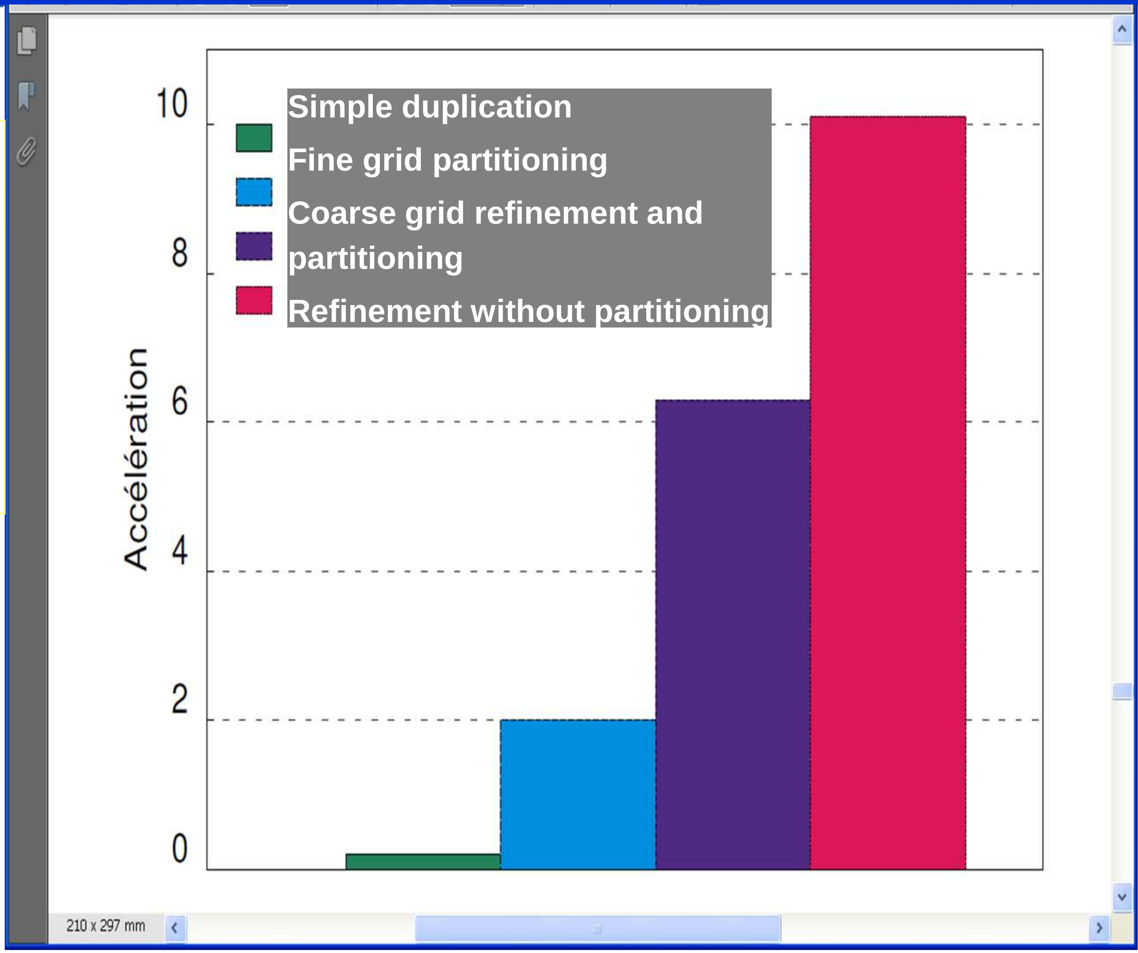
Measured efficiency on a Tesla 2050 (480 cores) and on a Tesla K20c (2200 cores) with respect to <u>one</u> node made of 2 Cpu Westmere (12 cores), OpenMP loop-based parallelism

Data model re-organization

in the FORTRAN / C / Cuda interface for GPU performance, function of the target architecture

Management of allocatable data structures

GPU technology Conference GTC2013
18-21 March 2013 San José



Max. Acceleration = 10 on a Tesla 2050 and 38 on a Tesla K20c, very good GPU scaling in successive generations GPU / CPU performance comparison :
2200 Gpu cores, 500 W, 5k€←→ 450 Cpu cores (38 nodes, 5 kW, 60 k€) ; issue on available memory

Some elements of Onera CFD roadmap 2030

2016-2022 :

- Prototypes for high order accurate schemes on HPC with demonstrations and interaction with industrial partners (Aghora, HO FV NXO scheme, …)

- elsA and Cedre on-going developments provided to industrial and research partners

2019-2022 :

- Start of a new HPC software development with the best of the prototypes and the knowledge and know-how (modules) from elsA and Cedre

2023-2030 :

- Progressive substitution of actual CFD software to new HPC software generation in the applied domain

All these studies performed in interaction with real physics and data provided by experiments (in particular Onera wind-tunnels)

- In 2015 start of a data assimilation Onera project

Water-Tunnel, ©Onera/Henri Werlé